Unlocking the Climate Record Stored within Mars' Polar Layered Deposits

Final Report

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0. Executive Summary

Two terrestrial planets in our solar system have climates driven by many complex factors including their orbits, geology, and volatiles. Mars offers a unique opportunity to study the effects of orbital changes in relative isolation. The recent (Myr to 10s of Myr) orbit of Mars has undergone large variations relative to changes on Earth or Venus. These variations have driven climate change in the absence of other complicating factors such as geological activity, large impacts or volatile loss from the planet. Although Milankovitch cycles also operate on Earth's climate, their effects are complicated by the oceans, life, active volcanism, and, more-recently, anthropogenic forcing. In the near-future, thousands of terrestrial exoplanets will be discovered and knowledge of their orbits and atmospheric compositions will be obtainable. Mars presents our best opportunity to study the effects of orbital change on bodies both in within our solar system and beyond.

Mars possesses a record of its recent climate in icy layers analogous to terrestrial ice sheets. The North and South Polar Layered Deposits (NPLD & SPLD) of Mars each contain thousands of observed layers in stacked sheets exceeding thicknesses greater than 2 km. HiRISE imagery of layer exposures on shallow slopes allow layers as thin as a few decimeters to be resolved, although pervasive sublimation lag deposits and camera resolution may hide thinner layers. Each of these layers contains information on the climatic history during its deposition. In decreasing abundance, the PLD are composed of water ice, dust, salts, geochemical weathering products, trapped gasses, and other materials including cosmogenic nuclides. Materials from stochastic processes, such as impact ejecta and volcanic ash fall, may also be included in some layers. With detailed measurements of layer composition, it may be possible to extract age, accumulation rates and likely atmospheric conditions and surface processes at the time of deposition.

During a two-part workshop of more than 35 Mars scientists, engineers, and technologists, hosted at the Keck Institute forf Space Studies, we focused on determining the measurements needed to extract the climate record contained in the polar layered deposits of Mars. The group converged on four fundamental questions that must be answered in order to extract the most information possible from the record and the measurements required to answer these questions.

1. *What are present and past fluxes of volatiles, dust, and other materials into and out of the polar regions?*
2. *How do orbital forcing and exchange with other reservoirs, affect those fluxes?*
3. *What chemical and physical processes form and modify layers?*
4. *What is the timespan, completeness, and temporal resolution recorded in the PLD?*

Each question relates to an important part of forming a polar ice layer. Addressing the first question is necessary to determine what materials are available for layer formation. The second question focuses on external drivers on the planetary climate and availability of materials that can be trapped. The third question directly relates to layer formation, from atmospheric deposition to modification after emplacement. The final question asks what information is available to assign dates to the layers and unlock the climate record.

Answering one question in isolation is insufficient, and a series of missions attempting to extract the climate record must address all four questions to accomplish the goal of determining the climate record on Mars. Further work requires a combination of measurements from orbit and the surface, modeling, and laboratory investigations. We have identified mission concepts that could best address these questions.

In order to answer Question 1, a polar orbiter capable of measuring wind speeds, vertically resolved atmospheric composition (especially water vapor abundances), temperature, and surface frost is required. The orbiter must operate for at least one Mars year in order to determine the seasonal cycle of available materials. Instruments required to answer this question were identified as a sub-mm sounder, thermal-infrared sounder, and a wide-angle imaging system.

Question 2 deals with the availability of surface water and carbon dioxide reservoirs at different times. To address this question, an orbital mission should have an instrument capable of measuring depth to, concentration of, and thickness of any subsurface ice on Mars. Our study determined that a radar sounder at much higher frequencies than currently available is the most capable instrument to achieve these measurements. A second, polarized Synthetic Aperture Radar (SAR) mode is required to directly detect the presence of water ice within a few wavelengths of the surface and provide maps of such.

Question 3 requires measurements to be taken at the surface that record atmosphere-surface interactions and active layer formation on the residual ice cap on top of the PLD if it is occurring today. Additionally, a subsurface component should assess post-deposition modification, and a drill will be required to access and deliver this material to proper instrumentation.

For Question 4, both landed and orbital assets are required. An orbital radar sounder would be adequate to match the vertical resolution of our highest-resolution cameras. This would establish lateral continuity between exposures and provide accumulation history across each PLD. In a separate mission, these measurements can be "ground truthed" by a method that can access many vertical layers of material, comprising thousands or millions of years of history. Two such ideas are to take a drill capable of boring > 100 m vertically, or a capable rover that can drive down the low-inclination spiral troughs and sample material every ~0.5 m vertically.

We propose the following Mars Polar Research Program: one orbiter to make atmospheric and subsurface measurements; a set of small-sat landers capable of measuring the local environment, either atmospheric or surface/subsurface; a small Discovery or New Frontiers-class lander with atmospheric sensors and meter-class drilling capabilities for measuring the local environment and assessing what materials are available for age dating; and finally a flagship-class mobile mission capable of sampling hundreds of meters of vertical stratigraphy.

1. Background

1.A Mars Polar Science Overview and State of the Art

1.A.1 Polar ice deposits overview and present state

The poles of Mars host approximately one million cubic kilometers (Smith et al. 2001) of layered ice deposits. Discovered by Mariner 9 imaging (Murray et al. 1972), these Polar Layered Deposits (PLD) have long been thought to record martian climate in an analogous way to terrestrial polar ice sheets. Both PLD are composed primarily of water ice (Grima et al. 2009) but contain dust up to a few percent of their total mass, as well as materials potentially related to specific geologic events, such as volcanic ash and impact ejecta. The vertical and horizontal distribution of these materials are thought to record atmospheric conditions including temperature, relative humidity, and aerosol dust content.

This iconic PLD layering is visible through radar sounding and visible imaging of bed exposures in troughs and scarps. Although the surfaces of the PLD are among the flattest and smoothest surfaces on Mars, they are bounded by steep scarps that typically expose up to a kilometer of vertical layering. Additionally, in the interior of the PLD, arcuate troughs expose a few hundred meters of bedding, which orbital imagers can observe. The bounding scarps appear to be erosional in nature, with active erosion observed at the steepest north polar examples (Russell et al. 2008). However, geologic structures within the PLD indicate that the internal troughs are constructional features, and that they experience erosion on their steeper equatorward facing walls, leading them to have migrated 10s of kilometers poleward as the PLD accumulated (Smith et al. 2010).

Variations in the orbital configuration of Mars lead to climatic variations, which are thought to be recorded in the PLD. Modeled The orbital parameters whose oscillations primarily drive these climatic changes are the planet's obliquity, orbital eccentricity, and argument of perihelion. The orbital solution goes back 20 Myr (Laskar et al. 2004). Obliquity cycles have characteristic timescales of ~120 kyr and ~1 Myr, eccentricity varies on timescales of ~1.2 Myr, and the argument of perihelion has a precession cycle of ~51 kyr. Over the last 20 Myrs, the obliquity of Mars has varied between 15 and 45 degrees (Laskar et al., 2004). High values of obliquity mean that the poles receive more sunlight on average than the mid-latitudes, which leads to ablation of polar ice. Conversely, low obliquity promotes accumulation of polar ice. The present obliquity is around 25°, which is low enough that the average insolation at the poles is lower than at the mid-latitudes, but high enough that the net mass balance that is difficult to distinguish from zero (Bapst et al. 2018). Recent obliquity variations between ~15 and ~35° straddle this value and may have led to large variations in the rate of polar accumulation. There are multiple angular unconformities in the stratigraphic record (Tanaka 2005) that show periods of net ablation have occurred, and extremely dusty layers may be sublimation lag deposits that represent disconformities in the record (Fishbaugh et al. 2010). Orbital solutions (Laskar et al., 2004) also show that the mean obliquity between 5 and 20 Ma was ~35° – substantially higher than the ~25° from 4 Ma to the present. Unique solutions prior to 20 Ma cannot currently be derived, but statistical arguments show that a high mean obliquity is common and that the most probable obliquity over all of martian history is ~42 degrees (Laskar et al., 2002). Thus, the current thick polar deposits may be atypical compared to most of martian history.

The age of the PLD has been estimated to be between a few million years in the north to up to 100 millions of years in the south, on the basis crater counting and modeling. Impact craters on the uppermost surface of the PLD can yield a lower age limit. The NPLD crater record indicates that crater infill with ice is ongoing and is fast enough to erase craters 100 m in diameter over timescales of kyr to 10s of kyr (Banks et al. 2010; Landis et al. 2016). The SPLD crater record is consistent with a non-accumulating surface that is between 30 Ma and 100 Ma in age (Koutnik et al. 2002). Model simulations of polar ice stability provide another age constraint. Several studies, described in sections below, argue that the high obliquities prior to 4-5 Ma make ice accumulation at the north pole impossible prior to that time. This has been interpreted as an upper limit for the age of the NPLD. However, the insulating effects of lag deposits are incompletely accounted for in these studies and the obvious older crater retention age of the SPLD must also be reconciled with these conclusions.

In addition to the icy bedding that make up most of their structure, the PLD are partly covered with bright residual ice caps that interact strongly with the current climate. The north polar residual ice cap is exposed at the end of the spring after seasonal CO_2 and water frosts sublimate. Stereo imagery shows that it has less than a meter of relief, and a texture of light and dark patches (or ridges in some locations) in repeating patterns with a horizontal scale on the order of decameters. It also exhibits an evolution of ice grain size and albedo throughout the year (Langevin et al. 2005; Brown et al. 2016). Fine-grained seasonal frost that accumulates in the Fall/Winter sublimates in the spring and summer and older large-grained ice is exposed for a portion of the summer, suggesting that net ablation is currently occurring (Langevin et al. 2005). However, this large-grained ice is dust-free, so ablation has not been significant enough to produce a lag deposit and ice is clearly currently accumulating within polar impact craters (Landis et al. 2016). At the south pole, the SPLD possess a partly buried reservoir of CO_2 ice (up to 1 km thick) that is comparable in mass to the current CO_2 atmosphere of the planet (Phillips et al. 2011; Bierson et al. 2016; Putzig et al., 2018). This CO_2 ice is capped by a water ice layer on top of which a much smaller (~1% of the current atmosphere) surface CO_2 ice deposit exists (Bibring et al. 2003; Byrne and Ingersoll, 2003; Titus et al. 2003). This deposit is known as the South Polar Residual Cap (SPRC), and it hosts a wide variety of sublimation-driven erosional features that have been observed to grow and change every Mars year. These rapid changes in the morphology and appearance of the SPRC are evidence of its sensitive interaction with the current climate. Not only do these sublimation features grow by by several meters per year (Thomas et al. 2009; 2016; Buhler et a., 2017), but summer dust storm activity has been observed to lead to distinctive bright halos on the edges of these features (Becerra et al. 2015), which may be associated with further wintertime condensation of CO_2 ice, and in turn allow this ice cap to survive for longer periods of time. This interaction, which we observe year to year, may be direct evidence for new PLD structures forming currently, although very different from the water ice beds that comprise most of the SPLD volume

1.A.2 Polar Layered Deposits formation and layers

During obliquity variations, the transfer of ice, aerosols, and dust from low latitudes to the poles causes the formation of alternating polar beds with variable ice purities. The bulk content of the NPLD is ~95% pure water ice (Grima et al. 2009). However, individual beds may be up to 50% dust (Lalich et al., 2017). The dust-rich beds may have formed during periods of high dust accumulation relative to ice, and/or during periods of ice loss. Dust-poor beds must have formed during times when ice deposition was high relative to dust accumulation (Hvidberg et al., 2012). It is therefore necessary to study the stratigraphy of the PLD in order to interpret the timing of deposition of each layer and build a climate record that ties bed sequences to particular insolation cycles in time. This will allow us to reconstruct the climatic history of Mars.

Observing the stratigraphic record

Accumulation at the PLD is not uniform in space (horizontally) or time (vertically). Both PLDs are thickest near the north pole and thinner at the margins (Smith et al., 2001); however the thickest SPLD is slightly offset from the pole. In the NPLD, there are clear patterns of local and regional accumulation that were affected by existing basal topography (Brothers et al., 2015) or other large structures (e.g. a buried chasma that has been filled in (Holt et al., 2010)). Additionally, unconformities, caused by deposition following erosion by sublimation or wind ablation, are numerous (Tanaka and Fortezzo 2012; Smith et al., 2016), and must be considered in the context of the stratigraphic column.

The differences in relative accumulation with geographic location, as well as post-depositional modification processes, affect the final state of the sedimentary record in the PLD that we can observe. Therefore, in order to detect the periodic signals corresponding to the astronomically-forced insolation, we need to be able to observe and describe intrinsic properties of the beds that make up the record, i.e., properties that relate most closely to the environmental conditions at the time of accumulation. These properties may include sintering rate, dust/ice ratio, or concentrations of different isotopes in a bed. On Earth, these properties can be extracted directly from ice or sediment core samples, but without such samples of martian ice, we must rely on remote sensing.

Remote sensing observations of exposed bed sequences

For the purposes of studying the internal stratigraphy of the PLD, we use orbital imaging at various wavelengths within the visible and infrared spectrum to extract information from the bedding outcrops exposed at the characteristic spiral troughs of the PLD (Cutts, 1973; Schenk and Moore, 2000; Smith and Holt, 2010; 2015). The information we can extract from these data are: brightness of layers, topography of the outcrop with stereo imaging, composition estimates from spectrometers and color-ratios.

Thanks to the High Resolution Imaging Science Experiment (HiRISE) (McEwen et al., 2007) on board NASA's Mars Reconnaissance Orbiter (MRO), we are able to extract reflectance and topographic information at the scale of the thinnest exposed beds (~ 1–2 meters). It is reasonable to assume that these properties are more closely related to the exposure of a particular layer than its intrinsic properties. However, the noticeable variation in topographic expression as well as brightness changes with depth in all of these outcrops, indicate that these properties must have some indirect relationship to the composition of the internal bedding. For example, a darker exposed layer may be related to a higher dust content in the internal layer, and a more protruding layer may also be associated with a high dust content that insulates and protects that particular bed from erosion compared to neighboring beds.

The main advantage of visible data from the outcrops is the meter–scale resolution. Nevertheless, these observations are limited to the top 400 – 800 m of the PLDs, i.e., to the maximum depths of exposures. Additionally, the outcrops are scattered throughout the extent of the PLD, and therefore, correlations must be made between a sequence exposed in one location, and one exposed in a different one, which is not a trivial endeavor (Fishbaugh and Hvidberg, 2006; Milkovich and Plaut, 2008; Becerra et al., 2016).

Observations of the subsurface structure with radar

Radar instruments like the Mars Advanced Radar for Subsurface and Ionosphere

Sounding (MARSIS; (Picardi et al., 2004)) on board the European Space Agency's (ESA's) Mars Express, and the Shallow Radar (SHARAD; (Seu et al., 2007)) on MRO, are sensitive to the dielectric properties of the target material. Ice is nearly transparent to radar waves, allowing the radio wave to penetrate to the deepest portions of the PLDs, as deep as 3.5 km, and permitting views of the internal structure.

Differences in silicic content (primarily dust, but possibly ash or ejecta) between icy layers will cause changes in dielectric permittivity that result in a change of the speed of the radar wave, causing a reflection that is recorded by the instrument (Nunes and Phillips, 2006). It is thanks to these data that we know that the bulk composition of the deposits is relatively pure ice, with 5 to 10% dust concentrations for the SPLD and NPLD, respectively (Plaut et al., 2007; Grima et al., 2009). The relationship between permittivity and dust content is not completely understood. For example, a series of thin, dust-rich beds may reflect the radar wave in a similar manner to a single, thick dust-rich layer (Lalich et al., 2017). Nevertheless, it is likely that the radar response is directly related to the dust content of the PLD beds at depth.

One difficulty in matching internal stratigraphy as measured with SHARAD to exposed outcrops observed with orbital imagers is that the vertical resolution of current radar observations is much lower than that of the latter. Where comparisons have been made, radar reflectors mimic the exposed layers in spectral frequency and geometry, most likely because both types of observations observe variable concentrations of dust (Christian et al., 2013; Becerra et al., 2017a). Yet, with the current radar assets, a bed-to-bed correlation between datasets is not possible, although attempts are being made to correlate groups of visible beds to radar reflectors (Becerra et al., 2018).

Large-scale geologic framework of the PLD

Establishing broad-scale relationships between layer packets and geologic units in the PLD provides the geologic framework within which the finer-scale stratigraphy must be analyzed and interpreted. Through a survey of vast amounts of imaging data from the Mars Orbiter Camera (MOC), the Thermal Emission Imaging System (THEMIS), MRO’s Context Camera (CTX), and HiRISE, coupled with topographic data from the Mars Orbiter Laser Altimeter (MOLA), Tanaka et al. (2007, 2008, 2012) searched for common characteristics and unconformities to develop a PLD-scale stratigraphic column and geologic map for both PLD. They derived the ages of the units from crater statistics and visual stratigraphy principles. From Tanaka et al., (2007; 2008; Tanaka and Fortezzo 2012), the units most relevant to PLD stratigraphy that we can identify at this scale include:

a) In the South:

- Aa4b: South Polar Residual Cap (SPRC), composed entirely of CO_2 up to 8 m thick that interacts with the atmosphere of Mars.
- Aa4a: SPRC lower layer composed of ~2 m of water ice.
- Aa3: CO_2 unit up to 1 km thick that is mostly cutoff from atmospheric interactions (Phillips et al., 2011; Putzig et al., 2018) estimated to be ~ 300 kyr old (Bierson et al., 2016).
- Aa2: High water ice layered deposits with a bulk dust content of up to 10%. This unit makes up the bulk of the SPLD. Cratering record estimates for the age of this unit range between 10 (Herkenhoff and Plaut, 2000) and 100 Myrs (Koutnik et al., 2002).
- Aa1: Oldest known water ice unit in the south, similar to Aa2 in composition.

b) In the North:

- Abb4: North Polar Residual Cap (NPRC). Roughly 1 m deposit composed of water ice, and thought to be currently accumulating (Brown et al., 2016).
- ABb3: Planum Boreum 3 Unit. A water ice unit 80-300 m thick that caps most low-sloping surfaces (Smith and Holt 2015; Smith et al., 2016).
- ABb1: Planum Boreum 1 Unit. A water ice unit that makes up the bulk of the NPLD (up to 2000 m) primarily exposed at spiral trough outcrops (Becerra et al., 2016; Byrne, 2009; Fortezzo, 2012; Smith and Holt, 2010). From stratigraphic analysis and
- accumulation models, it is thought to be about 4 – 5 Myrs old (Levrard et al., 2007; Hvidberg et al., 2012; Becerra et al., 2017b).
- Abbc = Planum Boreum Cavi unit. Uppermost unit of the dusty "basal unit" beneath the NPLD. The age of this unit is highly uncertain, with estimates ranging from Middle to Late Amazonian (Fortezzo, 2012; Tanaka et al., 2008). Recently, it has been found to be transgressive with the lowermost NPLD deposits (Ewing and Kocurik 2015; Nerozzi and Holt, 2017).

Image-based correlation of exposed sequences

Images of bed exposures can be used to define and classify discrete layer sequences based on their morphological properties. From there, continuous depth profiles can be extracted and directly compared to synthetic stratigraphies built with models of ice and sediment accumulation.

Studies by Fishbaugh and Hvidberg (2006) and by Milkovich and Plaut (2008) correlated spatially distinct sequences using the highest resolution images available at the time to propose the first relative stratigraphic columns for the NPLD and SPLD respectively. More recently, near complete imaging coverage of the PLD with CTX has allowed for individual beds to be traced hundreds of kilometers along the same trough, aiding the construction of stratigraphic columns that are valid for large areas of the PLD with a high degree of confidence (Becerra et al., 2016). Naturally, it is impossible to trace layers across different troughs relying solely on images of the exposures, in which cases the method of morphologically correlating bed sequences is preferred. Correlating different outcrops in this way involves an immense amount of detailed mapping work that can result in coherent stratigraphic relationships valid for large areas of the studied region. However, because of the periodic and repetitive nature of the PLD layering, bed sequences at different stratigraphic depths can appear very similar, adding a large amount of uncertainty to columns built solely with this method.

With layer-scale images and topography, continuous profiles of variations in brightness or topographic expression with depth can be extracted for particular exposures. These profiles can then be directly compared to climate proxies such as insolation or temperature changes with time (Laskar et al., 2002), or analyzed for periodic cycles that match those of the climate signals (Milkovich and Head, 2005; Perron and Huybers, 2009; Limaye et al., 2012; Becerra et al., 2017b). Properties such as bed protrusion, local slope, and brightness can be extracted from a Digital Terrain Model (DTM) of one location on the NPLD. Protrusion was defined by Becerra et al. (2016) as the difference between the actual topography in the HiRISE DTM and a linear fit to the slope of the trough wall in a particular segment of the profile. This quantity represents a proxy for the resistance to erosion of the various beds and is related to local slope, which is just the derivative of the elevation profile.

Radar-based stratigraphy

The ability to directly probe the internal structure of the PLD, made possible by subsurface sounding radar, signified a substantial step forward in the study of Mars Polar Science. The data returned by these instruments consists of two-dimensional radargram profiles that display the power returned at the detector along the track of the radar vs. the time delay between transmission of the radar signal and a particular surface or subsurface return. The time delay is roughly analogous to depth, but distortions occur due to surface topography and geometry of the observation, as well as the change in speed of the radar wave in different media. Therefore, time delay can be converted to depth using a simple time, velocity (modified by the material properties), and distance relationship.

If the depth or elevation difference between two points is known, then the dielectric value of the material can be estimated. Grima et al. (2009) followed this approach for the NPLD using MOLA measurements of the elevation difference between the top of the NPLD and the surrounding plains and SHARAD radargrams with returns from surface and the base of the NPLD. They calculated an average value of $\varepsilon' \sim 3.15$, typical of nearly pure water ice under martian conditions. Plaut et al. (2008) calculated a similar value for the SPLD using MARSIS data.

When radar data coverage is dense enough, various radar units can be mapped throughout the whole PLD, resulting in thickness measurements of prominent units and, in essence, a radar-based stratigraphy (Putzig et al., 2009; Smith and Holt, 2015). Additionally, a three-dimensional radar volume can be constructed for mapping structures in geometries not permitted with only two-dimensional profiles (Foss et al., 2017; Putzig et al., 2018).

Time-series analysis and cyclostratigraphy

A first step in the process of understanding paleoclimate is to search for periodicities in the data that match those of the climatic forcing mechanisms that are hypothesized to have led to the PLD accumulation. Assuming that time/depth-dependent functions like those in the stratigraphic profiles are forced by highly periodic functions like Mars' insolation history (Laskar et al., 2004), time-series analysis methods decompose the data functions into their periodic components. The two most prominent peaks in power correspond to the 51 kyr precession cycle of Mars' argument of perihelion, and to the 120 kyr oscillation of the obliquity. The two cycles have been compared to those in the stratigraphic data (Becerra et al., 2017b), and the spatial ratio was found to match favorably with the modeled periodicities.

Detailed stratigraphy of the NPLD

Stratigraphic studies of the NPLD are extensive, and data-based analyses have been generally accompanied by models of accumulation based on orbitally-driven climate cycles. Fishbaugh et al. (2010b) were the first to construct a stratigraphic column based on topographic and morphologic considerations from a single HiRISE DTM. They defined two principal types of beds or bedding packets: Marker Beds (MBs, so-called because of Malin et al. (2001)'s identification of the "original" Marker Bed in various sites on the NPLD with MOC), which are thick, dark and have a characteristic hummocky texture in the DTM they analyzed; and Thin

Layer Sets (TLS), which are sets of resistant beds, each ~ 1 – 2 m in thickness. In the spacing between MBs, the authors reported finding the 30 m periodicity previously observed by Laskar et al. (2002) and Milkovich and Head (2005); and in the spacing between thin layers in TLS, they observed the 1.6 m wavelength of Perron and Huybers, (2009). Later, Limaye et al. (2012) measured bed thicknesses and performed FFT analysis on brightness and slope profiles of 3 DTMs in the NPLD. They found a low variance in bed thicknesses, with the majority of beds measured to be just a few meters thick. Their spectral analysis confirmed the 1.6 m wavelength, but observed no 30 m wavelength. In addition, they observed a similar spacing between patterns in brightness profiles and patterns in local slope, showing that brightness may in fact correlate with topography in some locations.

With continued observations of the NPLD by HiRISE, the dataset of DTMs of the NPLD grew enough that correlations of layer sequences based on topographic, morphologic and reflective properties could be attempted. Becerra et al. (2016) used linear protrusion profiles taken from HiRISE DTMs, as well as analysis of orthorectified images to classify bed sequences in 16 DTMs across the PLD, extending the MB and TLS classification of Fishbaugh et al. (2010b). In addition, they used a combination of signal-matching of protrusion profiles and layer tracing across the bright and dark beds seen in CTX images to correlate a bed sequence present in 6 DTMs, resulting in a stratigraphic column of prominent MBs. Becerra et al., (2017b) performed wavelet analysis on brightness, slope, and protrusion profiles from the 16 DTMs. They identified two dominant stratigraphic wavelengths in all profiles: a common ratio of wavelengths of 1.98+0.15 in the stratigraphic data, systematically lower than the 2.35 ratio of the orbital signals in the 2 Ma insolation. This ratio matches that observed in synthetic stratigraphies generated by the accumulation model of Hvidberg et al. (2012), lending further credibility to that model. If one assumes that the surface is young or currently accumulating, then this results in mean accumulation rates of 0.54 mm/yr for the top 500 m of the NPLD.

Radar

One of the first major discoveries by SHARAD was the confirmation that the NPLD beds are laterally continuous throughout almost the entire extent of the dome, over 1000 km (Phillips et al., 2008). The continuous radar reflections observed typically consist of four packets of finely spaced reflectors separated by homogeneous interpacket regions of material with few or no dielectric interfaces. Phillips et al. (2008) explained the packet/interpacket structure by relating it to approximately million-year periodicities in Mars' obliquity and/or orbital eccentricity. Periods of high obliquity and eccentricity would have resulted in high dust accumulation from enhanced sublimation and therefore formed reflector packets due to varying silicic content. Periods of low obliquity amplitudes would have meant high ice accumulation and low dust storm activity, resulting in the interpacket zones that have fewer reflectors. Putzig et al. (2009) extended the previous work (see Figs. 9 and 10 in Putzig et al. (2009)) to suggest uniform deposition and erosion patterns were common throughout most of NPLD history.

Studies with the SHARAD dataset also allowed researchers to explain the formation of Chasma Boreale (Holt et al., 2010) and the onset, migration, and morphological diversity of the iconic spiral troughs (Smith and Holt, 2010; 2015).

Finally, Smith et al. (2016) used SHARAD data to identify and map a cap-wide unconformity in the NPLD. The material that accumulated post-unconformity was called the Widespread Recent Accumulation Package (WRAP). This package represents a change in

SHARAD reflector properties in the top <320 m of the NPLD. The model of Levrard et al. (2007) predicted that the upper ~300 m of the NPLD should have accumulated during the last ~400 kyrs, corresponding to a sharp drop in obliquity and average insolation amplitude, which would have signified large amounts of ice being transported from mid-latitudes to the north polar region, and the end of a martian “Ice Age”. Smith et al. (2016) found good agreement between predicted and measured thickness and between a predicted and measured volume since the last martian "ice age" and present day (Head et al., 2003). They ascribe the WRAP unconformity to approximately this point in NPLD history and estimate the age of the WRAP layer to be ~370 kyrs, implying a maximum accumulation rate locally of 0.86 mm/yr during that enhanced accumulation period and an average value closer to 0.32 mm/yr for the entire deposit.

1.A.3 Climate models and PLD formation

Introduction and Methodology

Models are critical tools for investigating the past climate of Mars. In particular, global climate models (GCMs) have been used to study aspects of the Amazonian climate and the formation of the PLDs. Since the Amazonian period is characterized by a solar luminosity similar to the current solar luminosity and an atmospheric mass comparable to what it is today, we can study the climate by considering how changes to the orbital parameters would affect the present-day Mars climate. Thus, the general methodology for these studies is to execute a GCM that does a reasonable job of reproducing the current Mars climate with modified orbit parameters (obliquity, eccentricity, argument of perihelion).

Modeling the Current Climate

The cycles of CO_2, dust, and water are the climate of Mars. Significant effort within the GCM community has been invested over the past few decades in improving how GCMs handle and predict these cycles. This requires the implementation of a wide range of physical processes that govern how dust, CO_2, and water cycle into, through, and out of the atmosphere.

Of the three climate cycles, the CO_2 cycle is the most straightforward to simulate in GCMs. Surface energy balance methods are used to compute surface CO_2 condensation and sublimation as CO_2 cycle into and out of the seasonal CO_2 polar caps. Atmospheric condensation of CO_2 is usually handled with a simple scheme in lieu of representing the more complex microphysical processes of cloud formation (Forget et al., 1999; Haberle et al., 2008; Guo et al., 2009), although recent work has been done on improving how CO_2 clouds are simulated in GCMs (Listowski et al., 2013; Dequaire et al., 2014).

Significant effort has been invested in improving the handling of water cycle physics in GCMs. The NPRC and NPLD outliers are generally considered to be the sole source of water to the atmosphere (Navarro et al., 2014), but some investigations have included a regolith source (Böttger et al., 2005). Cloud microphysical schemes have grown in sophistication to explicitly include the physics of nucleation, growth, and size-dependent gravitational sedimentation (Montmessin et al., 2002/2004). The inclusion of cloud radiative effects has proven quite challenging due to the many complex feedbacks involved, but significant progress has been made in realistically representing the seasonal cycles of water vapor and cloud (Navarro et al., 2014; Haberle et al., 2018).

The dust cycle remains the most challenging of the three climate cycles to simulate fully. Investigations that include the physics of dust lifting based on resolved surface wind stress and dust devils (and/or unresolved small-scale lifting) are able to capture general behaviors of the observed dust cycle but are thus far unable to realistically simulate others (Kahre et al., 2006; Basu et al., 2004; Newman et al., 2002). In particular, capturing the observed interannual variability of global dust storms remains elusive. In lieu of using fully interactive methods, studies that focus on other aspects of the martian climate generally use prescribed or semi-prescribed dust methods based. In these studies, the horizontal and/or vertical distribution of dust is constrained by observations (e.g., Mars Global Surveyor's Thermal Emission Spectrometer (TES) and Mars Reconnaissance Orbiter's Mars Climate Sounder (MCS) (Montabone et al., 2015). We must be cautious when we use the dust observations for past climate studies because it is unlikely that the seasonal patterns of atmospheric dust remain the same as orbit parameters change.

Current Understanding of Amazonian Climate

Modeling the Amazonian climate involves running GCMs that are generally capable of capturing the main components of the current Mars climate for different orbit parameters. Because GCMs are complex and require significant computational resources, it is not possible to explicitly simulate changing orbit parameters. Instead, combinations of obliquity, eccentricity, and season of perihelion are chosen to map out trends and branch points in the behavior of the climate. When designing these simulations, the total inventories and available surface reservoirs of CO_2, dust, and water must be taken into account. The effects of increasing or decreasing the obliquity are generally more substantial than changing the eccentricity or season of perihelion.

Obliquity variations have important consequences for the CO_2 cycle. As obliquity increases, the annual mean insolation at the poles increases. For obliquities greater than 54°, the poles receive more insolation than the equator. This drives more extreme seasonal variations in surface temperature and surface CO_2 ice. Overall, the global average surface pressure decreases with increasing obliquity because more CO_2 cycles into and out of the polar ice caps seasonally (Mischna et al. 2003; Haberle et al. 2003; Newman et al. 2005). At low obliquities (< ~20°), permanent CO_2 ice caps form and the atmosphere collapses (Haberle et al. 2003; Newman et al. 2005; Manning et al., 2006; 2019). In a collapsed state, the equilibrated atmospheric mass could be quite low (~30 Pa).

Obliquity variations largely control where water ice is stable on the surface. At low obliquities (<30°) when the polar insolation is low, water ice is stable at the pole and the atmosphere is relative dry (Mischna et al, 2003; Forget et al. 2006; Levrard et al. 2007). The hemisphere where the polar water ice resides is likely controlled by the season of perihelion, with the north favored when the perihelion occurs near southern summer solstice and the south favored when perihelion occurs near northern summer solstice (Montmessin et al., 2007). At moderate obliquity (30-40°), water becomes stable in the middle latitudes and the atmosphere is considerably wetter (Madeleine et al. 2009). At high obliquity, water ice is destabilized from the poles and becomes stable at low latitudes (Mischna and Richardson 2005 Forget et al. 2006; Levrard et al. 2007). An important final point here is that the radiative effects of water ice clouds have significant effects, particularly at moderate to high obliquity. Models predict optically thick clouds that form up high, which allows them to significantly warm the surface, enhance the mean circulation, and produce significant snowfall (Madeleine et al 2014; Haberle et al. 2012; Kahre et al., 2018).

Increasing obliquity significantly enhances predicted dust lifting and atmospheric dust loading. As obliquity increases, the Hadley cell is enhanced due to an increased equator-to-pole temperature gradient. The stronger return flow from the overturning circulation increases surface stress and thus wind-stress dust lifting (Haberle et al., 2003). Once dust is lifted, positive radiative/dynamic feedbacks further enhance the Hadley cell and dust lifting (Newman et al., 2005). While this predicted behavior is robust, there are potential caveats that must be considered. The first is the incorrect assumption that an infinite amount of surface dust is available for lifting everywhere on the planet. The second caveat is that early dust cycle simulations at high obliquity did not include water ice clouds. Clouds can scavenge dust and provide additional radiative/dynamic feedbacks that need to be fully understood.

Modeling the Polar Layer Deposits

The PLDs contain a record of the martian climate over time, so it makes sense that realistically modeling this record will require the use of models that are capable of modeling those evolving climate states. While there have been some attempts to use results (or general behaviors) from GCMs to self-consistently model the PLDs, this process has proven very challenging due to the complexities of the processes involved.

The most comprehensive published attempt to do this so far is by Levrard et al. (2007). In this study, GCM-predicted polar ice deposition and removal rates over a range of obliquities were used in combination with the computed obliquity history from Laskar (2004) over the past 10 million years to quantitatively track the evolution of polar surface ice reservoirs. The study found that the north cap could begin growing about 4 million years ago. The authors identified a paradox in their results, whereby only ~30 layers could have been generated by the changing obliquity during the past 4 million years, which is inconsistent with the visible layering of the NPLD but similar in order to the number of radar reflectors observed. This is likely because the amount of dust deposited in the polar regions (forming layers) varies on shorter timescales. That study Levrard study was based on an early GCM that contained a water cycle but not an interactive dust cycle. Interactive dust cycle studies suggest that the amount of dust deposited in the polar regions could vary significantly with varying orbital configurations (e.g., Newman et al., 2005). Fully coupled dust and water cycle simulations, like those presented in a preliminary form in Emmett et al. (2018), will further our understanding of how the PLDs have formed due to orbit-driven variations in the martian climate.

1.A.4 Terrestrial Climate Studies Using Ice

Terrestrial glaciers and ice sheets provide accessible field sites that can connect our understand of local processes to those on Mars. They represent a key component of the Earth climate system and interact dynamically with climate through several different processes. During glacial cycles, growth and retreat of glaciers in the northern hemisphere enhances the effects of climate changes through the ice-albedo feedback. In the present warming climate, surface melting and mass loss is further enhanced during summer due to the darkening effect of meltwater and dust at the surface of retreating glaciers and ice sheets. Increased discharge from marine terminating glaciers due to warm ocean temperatures may subsequently influence ocean circulation with global effects. Three key themes related to terrestrial glaciers and ice sheets stand out in modern terrestrial climates studies: understanding the glacial cycles of the Pleistocene, deriving the paleo-climatic history from the ice core archive, and estimating the mass loss from glaciers and ice sheets and their contribution to sea level increase.

The general flow pattern of ice sheets

On Earth, ice sheets form when climate conditions allow snow to accumulate at the surface over thousands of years, and they initiate and grow from mountainous areas that are colder than lower elevations. In the large terrestrial ice sheets, ice accumulates in the interior by snowfall, ice flows slowly towards the margin as the ice sheets spread due to gravity, and ice is lost along the margins by surface melting and run off or by discharge into the ocean from marine terminating glaciers. Although ice sheets respond to climate changes on longer and shorter timescales, they may gradually reach a steady state where snow accumulation is approximately balanced by discharge and runoff. The large ice sheets of Greenland and Antarctica were estimated to be close to steady state in the year 2000, at which point they began losing mass. In the high-elevation interior of these vast ice sheets, the ice sheets are more than 3 km thick and built up by layers of past snowfall. The layers have been compressed into glacier ice and thinned as they gradually sank into the ice sheet, and they were stretched as the ice moved slowly towards the coast. Climate proxies from ice core drilled through these layers need to take into account the thinning and stretching of the layers due to flow.

Transformation of snow to ice

Freshly deposited snow in the interior of the Greenland or Antarctic ice sheets has a density of 300-400 km m^{-3}. Density variations in the top tens of meters of the snowpack (firn) reveal an annual stratigraphy due to temperature and impurity content as well as individual events, e.g. wind crusts formed by packing action of wind on previously deposited snow or summer melt layers. Within the top 60-120 m, the firn gradually transforms into glacier ice with a density of 830 km m^{-3}. Flow and compaction of air bubbles below the firn-ice transition, increase the density further to 920 km m^{-3}, which remains approximately constant at greater depths. The depth of the firn-ice transition depends mainly on the mean annual temperature and the rate of snowfall. In the interior of the Antarctic ice sheet where the accumulation rate is 2-5 cm of ice/yr and mean annual temperatures below -50°C, the firn-ice transition occurs in a depth of >100 m. In the interior of the Greenland ice sheet, the accumulation rate is 15-30 cm of ice/yr, the annual mean temperature is around -30°C, and the firn-ice transition occurs in a depth of 70-80m. Glacier ice contains air bubbles with samples of the atmosphere from the time of the bubble close off and are used to document variations in past atmospheric composition (Cuffey and Paterson, 2010).

Composition, stratigraphy and timescales

Terrestrial ice sheets generally consist of nearly pure water ice with a small impurity content. Impurities originates from aerosols or particles deposited with the snow. Impurity records have an annual variation related to the atmospheric circulation and transport or are related to specific events, e.g. volcanic eruptions or forest fires. The stratigraphy in ice cores is observed by the electrical conductivity measurement (ECM), by continuous high-resolution profiles of concentrations of chemical impurities using the continuous flow apparatus (CFA) method, or by concentration of dust particles. ECM is a measure of the acidity of the ice and used to identify volcanic reference horizons due to their high concentration of sulfuric acid, and climate transitions due to the shifts in impurity concentrations and thereby changes in conductivity. CFA provides multiple continuous records of impurities and thereby allow identification of annual layers. In Greenland, the annual accumulation rate is sufficiently high to preserve an annual signal, and it is possible to detect the seasonal cycle in several impurity concentration records, e.g. insoluble dust, Ca^{2+}, NO_3^-, ECM. Insoluble dust particles from continents are carried by winds through the troposphere and deposited over the ice sheets. The particles typically have a size of order 0.1-2 µm and a bulk dust concentration of 50-200 µg per kg of ice in the interior of Antarctica and Greenland, respectively. During glacial periods, the concentration of continental dust increases by a factor of 10-100 (Greenland) and a factor of 20-50 (Antarctica). In Greenland, the dust concentration in glacial ice is high enough to influence the crystal size, and layers of high dust concentration are associated with small crystals. Crystal size is generally in the order of 0.1-1 cm^2 and increases with depth but drops at the Holocene-Pleistocene transition with a factor of 2. Although the dust is not visible by itself in the glacial ice, dust-rich layers can be identified in the visible stratigraphy of ice cores as cloudy bands. The visible stratigraphy in Greenlandic ice cores has revealed annual layers in the glacial ice down to a resolution of 1 cm (Cuffey and Paterson, 2010)

In Greenland, ice cores have been dated accurately by layer counting back to 60 kyr ago using a combination of visible stratigraphy, concentration of dust and chemical impurities. In the interior of East Antarctica, the annual accumulation is only few centimeters and annual layers cannot be identified. Ice cores in East Antarctica are dated from a combination of reference horizons with dates transferred from Greenlandic ice cores or other paleoclimatic records and ice flow modeling, taking into account thinning of layers due to flow and using consistent relations between climate and snow accumulation rate.

Radar stratigraphy

Radio-echo sounding is used to map the stratigraphy of terrestrial ice sheets. The stratigraphy in the top tens of meters is mapped with snow radar systems, employed from the surface with ground penetrating radar (GPR) systems or from airplanes carrying radar systems. The snow structure of the dry snow zone in Greenland has for example been mapped with an airborne Ku-band synthetic aperture radar (SAR) system and linked to in-situ observations from shallow ice cores and pit studies. The observations reveal the annual layer structure in the top 15-20 meter related to density variations in the firn, which forms due to seasonal variations in temperature, snowfall and impurity concentrations. Repeated surveys over several years show how layers sink into the ice sheet and new layers form at the top and allow detailed mapping of spatial and temporal variations of the annual snow accumulation (Simonsen et al. 2013).

In general, the radar stratigraphy of ice sheets arises from transitions in the bulk electrical conductivity of the media due to density variations, volcanic reference horizons, or climatic transitions associated with changes in impurity concentration of the ice. Deep internal radar layers have been linked to ice cores and dated using ice core timescales (e.g. MacGregor et al 2015). In Greenland, they are associated with abrupt climate transitions during the last glacial, known as Dansgaard-Oeschger cycles, or with glacial-interglacial transitions. In both Greenland and Antarctica, echo-free zones occur. In Greenland, ice deposited during the last glacial maximum between approximately 15 and 30 kyr BP contain no distinct radar-echo layers, possibly due to a generally high level of continental dust ($CaCO_3$ and Ca^{2+} ions), which neutralizes any volcanic acidity peaks during that period. The oldest ice in both Greenland and Antarctica are echo free or have a few blurred layers, and here it has been suggested that flow effects in these deep and old layers could have smeared out the transitions, e.g. by thinning layers or shearing and folding layers of different rheology. The internal radar layers show the past surfaces of the ice sheet as they sink down and are subject to flow, including thinning and stretching, local variations of basal melting, and large-scale evolution of the ice sheet and its flow pattern. Large structures of up to 50% of the ice thickness have been observed with radar in both Greenland and Antarctica and proposed to originate from large-scale folding or from refrozen meltwater plumes through a process similar to the formation of permafrost wedges (Bell et al 2011), but the origin of these structures is still not known.

The climate archive in ice cores

Paleo-climatic records from terrestrial ice cores have revolutionized the understanding of the Earth climate history and, together with ocean sediment cores, provided knowledge of glacial cycles and beyond. The key contributions of ice cores to the paleoclimatic community are their accurate and independent timescales as well as the unique information of past temperatures from oxygen isotopes (e.g. $\delta^{18}O$ and δD) and past atmospheric composition from air trapped within the ice (e.g. CO_2, CH_4) (Cuffey and Paterson, 2010). The ability to detect annual variations in many different parameters, such as oxygen isotopes, insoluble dust, and chemical impurities— and thereby identify and count each year—has contributed to understanding the timing and phases of climate changes in the past. Terrestrial ice cores contain an undisturbed stratigraphic record of ~100 kyr (Greenland) and ~1 Myr (Antarctica). Older layers are disturbed by flow or removed by basal melt. The climate archive of terrestrial ice cores is continuously expanded with new climate proxies and new techniques that makes it possible to detect more parameters and reduce sample size. One example is the continuous flow apparatus (CFA) technique. Ice is continuously melted along the ice core and analyzed in a semi-automatic wet-chemistry lab to provide records of isotopes, ions, cations, insoluble dust particles, conductivity, black carbon, etc., that contain information about atmospheric and oceanic circulation patterns, sea ice conditions, forest fires, far-field humidity, etc. The interpretation of these proxy records is done in combination with climate modeling and paleo-climatic records from other archives.

Selection of the drill site and recommendations for Mars

Ice core records from the interior Greenland and Antarctica are widely used to infer the climate history of Earth because the timescale is accurate and reliable and the records have been interpreted to provide the hemispheric or global climate history. The ice core records contain continuously deposited layers and allow age determination from measurements of constituents known to vary on annual timescales combined with reference horizons known from other stratigraphic records. Comparisons between ice cores or pits spaced over tens of meters in interior Greenland show significant local variations in snow accumulation rate due to surface roughness and wind effects, where snow is redistributed at the surface or removed due to wind scouring, but decade-averaged records are similar. Radar stratigraphy from the top meters of the firn to the deep (2-3 km) layers are continuous and smoothly varying and show similarly that the stratigraphy of the large ice sheets represents large-scale climate variations in the past, not local snow accumulation patterns.

Prior to an ice core drilling program, data is collected from the area and used for the drill site selection and planning of the campaign. Surface campaigns and radar surveys provide information on annual snow accumulation rate, ice thickness, ice flow velocity, surface conditions and local weather, as well as internal layer structure. In general, sites are preferred over smooth bedrock, with smooth, unfolded internal layers, no signs of basal melting or complicated flow over complex underlying topography (e.g. mountains), only little horizontal movement, with cold surface conditions, and no melting at the surface or at the base. The optimal site has undisturbed layers and no complicating upstream conditions.

On Mars, the polar caps are not as dynamic as the terrestrial ice sheets. Although the layers in the martian polar caps are not significantly influenced by flow, and no melting is expected to occur at the surface or the base, similar considerations are relevant for studying the stratigraphy or selecting a potential drill site as for terrestrial studies. Radar surveys show an internal layer structures with continuous layers across the polar caps, suggesting that these layers represent large-scale climate variations in the past, similar to the layers observed in the terrestrial polar ice sheets (Phillips et al., 2008). While the current annual snow accumulation on the polar caps of Mars is estimated from atmospheric observations of humidity in combination with climate models, it is not well known how or if the current annual rates of deposition and sublimation relates to the layer sequence. The deposited layers may not be related to the annual cycles, but to climate cycles on centennial, millennium or orbital timescales much longer than years. The resolution of the layering also depends on how post-depositional processes modify the surface of the layered deposits (Smith et al., 2013).

1.B History of Mars Polar Investigations

1.B.1 Orbiters

Spacecraft observations of the polar regions of Mars began with the Mariner 7 flyby in 1969. The seasonal caps were assumed to be water ice until this event. Prediction that the CO_2 atmosphere should condense in the winter (Leighton and Murray, 1966) was confirmed by Mariner 7 infrared spectrometer observations that recorded the appearance of forbidden transitions of CO_2 ice (Herr and Pimentel, 1969). Imagery of the polar regions began in 1971 with Mariner 9 and continued with the comprehensive coverage by Viking orbiters (1976-80). In the modern era, imagery at ever increasing spatial resolution has been obtained from the Mars

Global Surveyor (MGS), Odyssey, Mars Express and Mars Reconnaissance Orbiter (MRO) orbiters using the High Resolution Stereo Camera (HRSC), MOC, THEMIS, CTX, and HiRISE instruments. Infrared observations to observe surface properties began with multi-channel instruments (Infrared Thermal Mapper (IRTM) on Viking) and advanced to full spectroscopy and compositional measurements with the MGS thermal emission spectrometer (TES) and continues with Mars Express' Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité (OMEGA), and MRO's Compact Reconnaissance Imaging Spectrometer for Mars (CRISM). Infrared spectroscopy focused on atmospheric constituents and processes began with the Infrared Interferometer Spectrometer (IRIS) instrument on Mariner 9 and continued with MGS' TES, Mars Express' Planetary Fourier Spectrometer (PFS), and MRO's Mars Climate Sounder (MCS) (e.g. Smith, 2008). Gamma ray and neutron spectroscopy on Odyssey has been used to detect both buried ice deposits and the column density of the seasonal ice. Laser altimetry from the Mars Orbiter Laser Altimeter (MOLA) has been used to determine the thickness of the seasonal ice deposits. Radar measurements to probe the subsurface has been performed from both Mars Express using the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) instrument and MRO using the Shallow Radar (SHARAD) sounder. Table 1 summarizes these past spacecraft and instruments.

The history of Mars polar cap observations through the Viking era is summarized in Mars, the University of Arizona Press book, in chapters by James et al., (1992) and Jakosky and Haberle (1992). Approximately one decade ago, Titus et al. (2008) provided an update and review of new information emerging up to that point, summarizing martian polar processes for the Cambridge monograph "The martian Surface".

Optical and infrared observations have focused on annual processes, inter-annual variability, composition and physical state. This includes seasonal cap advance and retreat, mass wasting, mobility of high and low albedo deposits, geomorphology of features in the south residual CO_2 ice, the presence of H_2O, CO_2 and non-ice materials, and their grain sizes or optical path lengths. Stratigraphy is also a major component of image science.

Seasonal Processes – The most recent analyses of the seasonal cap cycle from Mars Color Imager (MARCI), TES, and MCS establish a martian decade of observations (Mars Years (MY) 23-32) (Calvin et al., 2015, Calvin et al., 2017) and allow creation of a climatological model average over many years (Piqueux et al., 2015). Spectrometer systems have studied the composition of the retreating cap, mapping water in both an annular ring at the cap edge and as a lag on the retreating north seasonal cap (Appéré et al., 2011; Brown et al., 2012). In the south, the properties of the "cryptic terrain" in the retreating seasonal cap, and transient bright halos surrounding pits in the residual CO_2 ice have been studied (Langevin et al., 2007; Schmidt et al., 2009; Becerra et al., 2015). The latest atmospheric sounding has demonstrated snowfall is an important process in forming seasonal caps (Hayne et al., 2014).

Residual Ices and Long-term Geomorphic Change – Both OMEGA and CRISM have observed the properties of the residual ice caps, noting grain size changes, layer properties, shifts between deposition and sublimation (Langevin et al. 2005; Calvin et al. 2009; Brown et al. 2016). In the south, water ice observed at the margins of the south residual cap has been modeled (Douté et al. 2007). To date little work has been done to model the compositional properties of the complex geomorphology of the south residual CO_2 ice (Thomas et al. 2009). However long term and detailed analysis using CTX and HiRISE has classified this surface into seventeen morphological units with varying thickness and inferred depositional timeframes, and it is suggested that well over 80% of the southern residual cap has been resurfaced in some

Table 1: List of NASA and ESA missions that collected data at Mars.

Spacecraft	Instruments for Polar Studies	Properties
Mariner 7 Flyby - 1969	TV Camera Infrared Spectrometer	RGB Filters 19 to 14.4 µm ~200x 100 km
Mariner 9 Orbiter 1971-1972	Imaging System	Wide and Narrow Angle
	Infrared Interferometer Spectrometer (IRIS)	5 - 50 µm ~110 km spot
Viking 1 & 2 Orbiters 1976 - 1980	Imaging System	~40 m to 300 m
	Inrafred Thermal Mapper (IRTM)	5 thermal bands and 1 solar (albedo) channel 30-170 km spot
Mars Global Surveyor (MGS) 1996-2006	Mars Orbiter Camera (MOC)	NA - B/W - 2-12 m/pix WA - RB - 240 m/pix
	Thermal Emission Spectrometer (TES)	5-50 µm 6 km spot
	Mars Orbiter Laser Altimeter (MOLA)	180 m spot size, 0.2 m vertical accuracy
Odyssey 2001 - Present	Thermal Emission Imaging System (THEMIS)	VIR - 5 channels 20 m/pix TIR - 10 channels 100 m/pix
	Gamma Ray Spectrometer (GRS)	600 km resolution of the upper 1 m
Mars Express 2004 - Present	High Resolution Stereo Color Imager (HRSC)	4 color and pan, stereo, 10 m/pix Super res B/W 2.3 m/pix
	OMEGA Spectrometer	0.36 to 5.2 µm, ~200 m to 1 km/pix
	PFS Fourier Spectrometer	1 to 45 µm, ~10 km spot
	MARSIS Radar Sounder	~100 m vertical res / > 2 km penetration depth
Mars Reconniassance Orbiter 2006 - Present	MARCI	5 color, ~ 1 km/pix
	CTX	B/W, ~ 5 m/pix
	HiRISE	B/W w/ color strip 25 cm/pix
	CRISM	0.36 - 3.92 µm, 18 to 200 m/pix
	MCS	8 channel, 4 to 6 km spots
	SHARAD	8-15 m vertical resolution / up to 2.5 km penetration

fashion in the last 40 Mars Years (Thomas et al. 2016).

Non-ice material composition and properties – Several studies have examined the distribution of hydrated materials, altered glasses and basaltic materials, and the origins of gypsum on the north polar dunes (Horgan et al. 2009; Horgan and Bell, 2012; Massé et al., 2012). Thermal properties have demonstrated that the north polar dune material overlies shallow ground ice or ice-cemented sands (Putzig et al. 2014).

Recent radar observations by MARSIS and SHARAD radar sounding have demonstrated that the transparency of the SPLD ice to radar signals equates to dust contamination of order 10 to 15% (Seu et al., 2007; Plaut et al., 2007; Zuber et al. 2007). Observations by SHARAD see a large "reflection free zone" in the interior that is interpreted as a large deposit of CO_2 ice (Phillips et al. 2011). Expanded coverage and analysis shows this unit has several layers that are inferred to be stabilized by interbedded and overlying layers of water ice (Bierson et al. 2016). Detailed three-dimensional modeling has suggested the long-term accumulation history of the NPLD and identifies buried structures (Foss et al., 2017; Putzig et al. 2018).

1.B.2 Landers

The polar regions of Mars have been a high-priority target for landed missions for decades. Since their discovery in Mariner 9 images (Murray et al., 1972), the polar layered deposits were suggested to contain a climate record, which could be accessed in at least a limited number of exposures (Cutts, 1973; Howard et al., 1982). High-resolution images from the Mars Global Surveyor's Mars Orbiter Camera (MOC) revealed much more extensive layered deposits than had been previously recognized, especially in the south polar region (Malin et al., 1998).

Mars Polar Lander. Landing site selection for NASA's Mars '98 mission was guided towards the south polar deposits, where remote sensing data revealed a vast volume of ice just beneath a layer of dust or regolith. This mission became Mars Polar Lander, which had primary science objectives to dig into the subsurface to search for water, to measure the atmospheric composition, and to survey the south polar layered deposits to better understand their formation mechanisms. Its landing site was located in a region 73 – 78°S and 170 – 230°W. In addition to the main lander, the Mars Polar Lander spacecraft also contained two penetrator probes, called Deep Space 2 (DS-2) designed to sample the atmosphere during descent, and the subsurface soil and ice layers following impact. Unfortunately, a malfunction in the Mars Polar Lander's descent stage caused the catastrophic loss of both the primary payload and DS-2 (Albee et al., 2000). Subsequent efforts to locate the lander using high resolution imaging have not succeeded.

Phoenix. Resurrected as the Phoenix mission, the Mars Polar Lander spacecraft was rebuilt and repurposed to a high latitude location. Launched in 2007, Phoenix landed at a position of 68.22°N, 125.7°W on May 25, 2008. Its primary purpose was to study the geologic history and habitability of subsurface water by sampling material at this high-latitude landing site. Although its location was over 700 km from the NPLD, the Phoenix mission's landing site was on top of a region with well-established ground ice, where remote sensing and model calculations had shown ice likely to be present in the upper few centimeters (Fanale et al., 1986; Mellon and Jakosky, 1993; Feldman et al., 1993; Aharonson and Schorghofer, 2006; Putzig and Mellon, 2007). Indeed, the robotic arm and scoop struck ice beneath a layer of loose, ice-free soil ~5 cm thick (Mellon et al., 2009). Furthermore, Phoenix detected apparent liquid droplets on its lander legs, which could be due to condensation or melting on deliquescent salts (Rennó et al., 2009). Significant exchange of water vapor between the surface and atmosphere was also detected by the lander's thermal and electrical conductivity probe (TECP; Zent et al., 2010).

1.B.3 Previous Concept Studies

In the past 15 years, multiple missions to the northern polar deposits have been proposed as part of either concept studies or spacecraft proposals to NASA. None passed beyond the proposal stage. They are summarized here to represent past polar community thinking on observational strategies. One can see that while the technology and exploration platforms have varied, the core observational strategies desired by the polar community has not.

Decadal Survey concept studies

In a mission concept study associated with the SS2012 Planetary Science Decadal Survey, Calvin et al (2010) identified how to use the following basic architectures for near-future polar missions: Discovery-class orbiters, New Frontiers-class orbiter, Discovery-class lander, New Frontiers-class lander, and New Frontiers-class rover.

Discovery-class orbiter

This mission concept is suited to two fundamental analyses at long timescales (> 1 Mars year): investigation of the current climate and seasonal cap properties, or investigation of surface energy balance and composition. The first investigation would focus on weather cameras and atmospheric sounding techniques, while the second would utilize mineralogy/spectroscopy measurements and an active sounder for observations during the polar night. Both investigations would be regional (cap-wide).

New Frontiers-class orbiter

This mission concept is similar to the Discovery-class orbiter, but could support both investigations and associated instrument suites outlined above with a single platform.

Discovery-class lander

This mission concept is suited to detailed (cm-scale) stratigraphic analysis of the layered deposits and the current surface-atmosphere interactions on a short (< 1 Mars year) timescale. It would land a stationary platform at the base of a stack of exposed polar layered deposits and examine the layers optically with remote sensing techniques such as imaging and spectroscopy. A meteorological package would be included. This analysis would be fairly local; layers exposed along the trough wall could be observed in multiple places from a stationary platform for an assessment of meters-scale variations.

Discovery/New Frontiers-class lander with subsurface access

This mission concept is suited to very detailed (mm-to-cm scale) chemical and stratigraphic analysis of the layered deposits and the current surface-atmosphere interactions on a short (<1 Mars year) to a longer (> 1 Mars year if using a radioisotopic power source) timescale. It would land a stationary platform on top of a stack of polar layered deposits and examine the layers via a drill and in situ measurement techniques. There are many variations of this concept, including thermal drill vs mechanical drill technology and taking measurements down-borehole vs from the surface platform. This analysis would be extremely local – a single drill location.

Two proposals for Discovery-class (Mars Scout) landers with subsurface access are described in more detail below. Neither were selected.

New Frontiers-class rover

This mission concept is suited to very detailed (mm-to-cm scale) chemical and stratigraphic analysis of the layered deposits and the current surface-atmosphere interactions on a short (<1 Mars year) to a longer (> 1 Mars year if using a radioisotopic power source) timescale. It would land a rover carrying a rock corer or drill, and collect samples for analysis throughout its traverse across exposures of layered deposits. This analysis could be semi-regional (on the scale of multiple km), depending on the distance traversed by the rover.

A similar rover concept was part of a NASA Vision study and is described in more below.

Thermal drill-based lander concepts

Three detailed mission concepts from the last 15 years have focused on accessing the stratigraphy within the northern polar deposits using a thermal drill, which melts a hole in the ice through the production of heat within the drill itself and descends on a tether as the hole deepens. Thus, the drill descends into the hole by the act of creating the hole. Analysis of the interior of the polar deposits must be done on the walls of hole as the drill descends using instrumentation fit within the thermal drill itself, or upon the resulting meltwater pumped through the tether to a instrumented surface platform. The three missions described here are each built around a different version of the thermal drill technology. Note that we describe the big-picture concepts of each mission but do not describe details of the instrumentation and drill technologies involved.

Cryoscout, Mars Scout Proposal

Cryoscout was proposed in 2002 by Principal Investigator Frank Carsey and team to the Mars Scout Program, for a 2007 launch opportunity. The overall mission concept was to repurpose the 2001 Mars Surveyor lander platform for an analysis of the northern polar stratigraphy via a thermal drill that would descend up to 80 m into the PLD (Zimmerman et al, 2002).

Mission overview

Cryoscout would have landed on the surface of the NPLD in late northern spring of 2008. A solar powered mission, it would have used a gimbaled solar array to take advantage of the continuous polar sunlight to conduct drill operations for 90 days (Zimmerman et al, 2002; Hecht and Saunders 2003).

The Cryoscout thermal drill (or "cryobot") was an active water-jetting system that was anticipated to descend at an average rate of 4 cm/hour (Hecht and Saunders, 2003). The front of the cryobot contained multiple heaters, water jet nozzles, and a pump bay. The cryobot would begin by passively melting the ice around its nose; as meltwater built up, the cryobot would pump meltwater into its interior and pressurize it to use the front water jets to remove particulates away from the front heaters. In the interior of the cryobot was also the instrument bay, with a window for imaging instruments and small chambers for meltwater analysis. The tether for the cryobot was carried inside the aft bay of the probe itself and unspooled as the probe descended; the fixed end of the tether was at the surface platform. Power for the cryobot and data from the cryobot were carried along the tether (Zimmerman et al, 2002).

The thermal drill would have descended in a 1 mm thick "melt-water jacket" and the tether fixed in place as the hole froze shut ~meters behind the cryobot (Zimmerman et al, 2002). This meant that measurement of fine-scale variations in layer stratigraphy and chemistry with depth would have been complicated by mixing of the meltwater and concentration of particulates as the drill descended (Hecht and Saunders, 2003).

Instrument suite

The instrument suite for Cryoscout was divided into a package in the cryobot probe casing, a set of instruments incorporated into the tether itself, and a package on the lander platform (all summarized from Hecht and Saunders, 2003).

- Within the thermal drill:
    - Imaging nephelometer to record the visible stratigraphy
        - 1-mm vertical resolution in nephelometer mode
        - full-color stereo images at 10 microns per pixel
    - A suite of electrochemical sensors to determine salt composition and abundance in meltwater
    - Isotopic laser hygrometer to measure variations in relative H and O isotopic abundance in meltwater
- Within the tether:
    - Distributed fiber thermometer incorporated into the tether to collect the time dependent ice temperature profile, including the thermal wave penetration in the top ~20 m and the geothermal heat flux below that.
- On the surface platform:
    - Stereoscopic imager to study the dynamics of polar surface, including atmospheric opacity and surface albedo
    - Surface version of the isotopic laser hygrometer to record the movement of water vapor, provide a baseline measurement of isotopic ratios, and monitor basic meteorology.

<u>Chronos, Mars Scout Proposal</u>

Chronos was proposed in 2006 by Principal Investigator Michael Hecht and team to the Mars Scout Program, for a 2013 launch opportunity. The overall mission concept was an update to the Cryoscout proposal that included two thermal drills, one shallow (10 m) and one deep (75 m) (Hecht, 2006).

Mission overview

Chronos had a similar mission profile to that of Cryoscout: using the 2001 Mars Surveyor/2007 Mars Pheonix platform to land in late northern spring for a solar-powered, 90-day mission. However, the thermal drill technology had evolved considerably, and the associated observational strategy was updated to match.

The Chronos thermal drill was a passive, dry-hole system that pumped meltwater up through the tether as the drill descended (Smith et al, 2006); it did not include the active meltwater jets of the Cryoscout thermal drill (Zimmerman et al, 2002). Similar to Cryoscout, the thermal drill was separated into multiple bays including a pump bay and an instrument bay, and the tether served as a pathway for powering the drill and for returning data from the drill. The tether did not unspool from the thermal drill but from the surface platform (Smith et al, 2006). It was anticipated to descend at rates of 20-45 cm/hour (Hecht 2006).

A significant new feature of the Chronos drill system was bringing meltwater to the surface through the heated tether. This meant additional measurements of the meltwater were possible due to not being required to fit instrumentation into the drill itself. Furthermore, the spatial scale of the mixing of meltwater in the tether was much smaller compared to that of the Cryoscout borehole, which translates to finer spatial resolution of meltwater-based measurements of variations in layer stratigraphy and chemistry (Hecht 2006).

Chronos was to carry two identical drills, one with a 10 m tether and one with a 75 m tether. The shallow drill was to be deployed first, allowing for a rapid assessment of near-surface stratigraphy. Operational lessons learned from the shallow drill could then be applied to the deployment of the deep drill (Hecht 2006).

Instrument suite

The instrument suite for Chronos was divided into a package in the thermal drill casing and a package on the lander platform (all summarized from Hecht, 2006).

- Within the thermal drill:
    - Imaging nephelometer to record the visible stratigraphy
        - 1-mm vertical resolution in nephelometer mode
        - full-color stereo images at 10 microns per pixel
    - Temperature sensor to determine the ice temperature profile during drill sleep periods (deeper drill)
    - Miniature seismometer that freezes into the ice to measure fundamental properties of the interior structure of Mars (shorter drill)
- On the surface platform:
    - Stereoscopic imager to study the dynamics of polar surface, including atmospheric opacity and surface albedo
    - A suite of electrochemical sensors to determine salt composition and abundance in meltwater
    - Isotopic laser spectrometer to measure variations in relative isotopic abundance of H and O in the meltwater
    - Meteorology package to characterize the surface fluxes of the polar deposits

<u>Palmer Quest, NASA Vision Study</u>

Palmer Quest was a NASA Vision Study under the direction of Frank Carsey in 2005, to determine how the application of key NASA strategic technology developments (e.g., advanced nuclear systems for planetary exploration) could be used to further NASA science goals (e.g., assessing the presence of life and evaluating the habitability at the base of the north polar deposits) (Carsey et al, 2005a). This makes it a very different sort of creature than the mission proposals such as Chronos or Cryoscout, which were designed for particular launch windows and budget envelopes.

Mission overview

Palmer Quest encompassed a multi-platform exploration of the north polar deposits, including a lander with a thermal drill to explore the layered deposits in situ, a rover to laterally explore the surface exposure of the layered deposits, and a surface station that would deploy some distance from the drill platform to measure surface fluxes and meteorological conditions (Carsey et al, 2005b).

Lander/drill platform concept and instrumentation

The lander for Palmer Quest had many purposes over the course of the mission. It first was to serve as the descent vehicle for all the components. Once the surface station and rover were deployed, it then served as the drill platform support for the thermal drill as well as communications relay for the drill and the surface station.

The thermal drill was a variation on the active water jet system of Cryoscout, but with a nuclear reactor inside the cryobot. The reactor would both create the heat for drilling and power the cryobot, the drill platform, and the surface station via cabling in the tether (Carsey et al, 2005a). The cryobot would melt down through several km of ice to the contact with what was at the time called the Basal Unit, where it would monitor the meltwater and look for astrobiologically promising changes in chemistry (Carsey et al, 2005b).

All scientific instrumentation would be contained within the thermal drill, including a descent imager, organic and inorganic sensors, raman spectroscopy, and a mass spectrometer (Carsey et al, 2005a).

Surface station concept and instrumentation

The surface station component of Palmer Quest was intended to observe the formation of the top surface of the polar deposits by characterizing the polar surface/atmosphere interactions, and thus had to minimize radiative/conductive/convective interactions of the station with the surface and the atmosphere. It consisted of a deployable tetrahedral base structure several meters in height. The base structure supported a suspended platform to monitor time-varying atmospheric conditions, and a scanning platform in close proximity to the top surface of the polar cap (Carsey et al, 2005a).

The surface station would be connected to the drill platform by a cable providing power and data transfer between the two components. It would be deployed 100 m away from the drill platform in order to minimize the thermal effect of the drill platform on its measurements. It would operate for at least 2.5 Mars years (Carsey et al, 2005a).

The instrument suite on the surface station included temperature and pressure sensors on the base frame, a laser altimeter and camera to monitor changes in the polar surface with time, and other meteorological instrumentation (Carsey et al, 2005a).

Rover platform concept and instrumentation

The Far Roving Arctic Mission (FRAM) rover component of Palmer Quest was intended to provide regional context for the subsurface measurements and to link the subsurface measurements to orbital spacecraft observations. It would operate for 100 days. It had a radioisotope power source, a four-wheel drive system with inflatable wheels, and a 10 cm ultrasonic percussive drill. FRAM was to have deployed from the lander, dragged the surface station 100 m away from the lander, and proceeded to drive across multiple troughs. At regular spatial intervals along its traverse, the rover would autonomously stop to perform scientific observations including post-drill science; the rover would not have been commanded with a customized set of observations every day (Carsey et al, 2005a).

The instrument suite of the rover would be divided between those on the rover deck and those on an instrument deployment arm. Post-drilling, the instrument deployment arm would position its instrument suite for down-hole measurements (Carsey et al, 2005a).

- On the rover deck:
    - Science imager for morphological assessment of the surface
    - Engineering cameras for navigational purposes
- On the instrument deployment arm:
    - Tunable diode laser spectrometer
    - Microscopic imager
    - Raman spectrometer
    - Chemical sensors

While none of the mission concepts outlined above made it past (or in many cases, to) the proposal stage, common themes of exploration are clear: accessing the local subsurface stratigraphy, placing it in the regional context of the broader polar deposits, and relating it to the seasonal evolution of the polar surface.

2. Study Objectives and Overview

2.A Aims and Objectives of this Study

Goals of this Study Program: Investigate and interpret the climate signals recorded in the PLD, either from remote sensing or in situ analysis. Although significant progress has been made using data from missions such as MRO combined with climate modeling studies, efforts to link PLD properties to climate processes are in their early stages, and there is still much ambiguity. We therefore propose a study program to identify the key measurements needed to fundamentally advance Mars climate science.

To accomplish the study goals, we brought together experts to: 1) Establish the "big picture" questions in Mars climate science that could be addressed by investigating the PLD; 2) Identify and prioritize measurements that could address these questions; 3) Define instruments or missions to perform the highest priority measurements; 4) Identify key technology needs for near-term development and a long-term pathway for proposing a mission to the PLD.

Although this study program opened with an invitation to think broadly and creatively, we envisioned a focus on landed missions capable of chemical and isotopic analysis. This type of investigation would fundamentally change the way Mars climate science is done, because we would have “ground truth” measurements that could be tied to existing and future orbital/ remote sensing observations. Detailed knowledge of the depositional, erosional, and structural processes acting on the PLD throughout their history would resolve uncertainties and bring the recent climate of Mars into sharper focus.

We seek a path to performing the first paleoclimate study of another planet with detailed analysis of layers in the polar ice caps of Mars. To find and map out this path, our study program will bring together experts on Mars polar environments; Earth’s climate, as recorded in ice cores; and space instrumentation and mission design. These experts will come up with an approach to revolutionize understanding of Mars’ climate history through investigation of the PLD using recently developed technologies and creative approaches.

Whereas the major focus of the current Mars program is on the ancient habitability and possible present-day liquid water activity, we see an opportunity to look at the geologically recent (20 Myr) habitability and climate history that is stored in the PLD. Sampling the PLD could provide a record of the past several million years of climate that would be unprecedented and incomparable in its detail. Specifically, linking the PLD properties to astronomical climate-forcing mechanisms (obliquity, eccentricity, etc.) has the potential to impact the whole field of planetary climatology.

The PLD have been an important target of investigation since the 1970s, when they were discovered to have layers thought to contain a record of accumulation and erosion of ice (Murray et al., 1972). Still, the polar science community only makes up a small fraction of the larger Mars research community. In the current Mars Exploration Program Analysis Group (MEPAG) goals (of which there are 4) polar science appears directly under both geology and climate. Exploration of the poles could also advance MEPAG’s technology goal, and a climate record informs us of habitability and thus also advances MEPAG’s life-science goal. Although polar science is important enough to address every MEPAG goal, it is not a standalone goal and thus it is difficult for polar science to compete with dedicated geology- or climate-driven missions and instruments.

Our approach is to make the PLD a primary target for further research. Recent discoveries (see below) have shown that there is abundant record of Mars’ history within these deposits and that advancements in this field, especially major advances in extracting detailed climate records, will benefit the entire research community, including atmospheric scientists and geologists.

From a scientific point of view, this is the opportune time to set the direction of future exploration of the PLD. The Mars Polar Science community held a conference (Smith et al., 2018) in 2016 that distilled and summarized many years of research performed on the datasets of the MRO mission and others. MRO represents the last in a line of polar-orbiting missions that have enabled seminal advances in Mars polar science. However, since MRO launched, Mars missions have centered on large rovers that investigate equatorial sites representing ancient Mars. Thus, we are at a turning point in the exploration of the PLD where existing data have been well-studied and new data are many years away.

Technological developments have also occurred in the past decade that make a polar mission more technically feasible and affordable than in the past. Entry, descent and landing technology has evolved to include new methods of placing large payloads on the surface with greater location accuracy (such as airbag cushioned rolls used on the Mars Exploration Rovers and the sky crane used for the Curiosity rover and planned again for the 2020 rover).

Much progress has been made in constructing theoretical models that relate different climates to PLD accumulation and ablation (Levrard et al. 2007; Hvidberg et al. 2012). Several recent studies have compared MRO observations of the layers to these models and they show broad agreement on the recent accumulation rate of the northern PLD (Becerra et al., 2016; Landis et al., 2016; Smith et al., 2016). Thus, we are ready to place layer properties (and the climatic information they contain) measured in a future landed investigation into a chronological and climatological framework.

2.B First Workshop

Significant new progress and breakthroughs using data from missions such as MRO combined with climate modeling studies become less likely with time. We therefore convened a study program at the Keck Institute of Space Science to identify the key measurements needed to fundamentally advance Mars climate science. The objectives of the first workshop were to establish the most effective methods of investigating and interpreting the layers of the NPLD in search of clear climate signals.

Researchers using optical and radar instruments have made many advancements in recent years and have answered long-held questions about the formation of the NPLD. With these advancements come new questions and hypotheses to test. For example, in 2016, two papers addressed specific questions about the climate record. The first used radar sounding in an attempt to put an exact date on an unconformity tracked across the entire NPLD (Smith et al., 2016). This paper compared the volume of ice accumulated since that unconformity to published estimates of ice transfer to the poles during the last major retreat of mid-latitude ice, ca 370,000 years. Those volumes were less than a factor of two apart, lending credence to the interpretation that this unconformity represented the last maximum in mid-latitude ice extent. On that time scale, the total amount of ice on Mars doesn't vary by much, but the surface area coverage decreases as the PLD gain material through transportation from the mid- and low-latitudes. The second study compared overlapping periodicities in NPLD stratigraphy to predicted climate forcings and found that there was a good agreement (Becerra et al., 2016). These results lent observational support to a previously published model (Hvidberg et al. 2012) that related depth in the PLD to age. Thus, recent studies have moved forward to the point where ages can be assigned to layers with and specific hypothesis can be tested by new observations.

We brought together experts to determine what major science questions remain to be answered on this topic. After defining the top-level science questions, workshop attendees were asked to identify and prioritize measurements that could address these questions, define instruments or mission concepts to perform the highest priority measurements, and identify key technology needs for near-term development and mission proposal.

2.C Second Workshop

The second workshop, held in November 2017, focused on designing mission concepts that could address the major science questions within the context of the current Decadal Survey, "Visions and Voyages" (Council, 2011). This document did not advocate for a New Frontiers or Flagship mission to the poles, but it did stress the importance of Mars polar investigations related to ice and climate and spelled out the need for a new polar orbiter.

In that context, we focused on designing missions that could fit within the NASA Discovery and Small Innovative Missions for Planetary Exploration (SIMPLEX) programs i.e. programs that were large enough to develop significant payloads that could reach Mars surface or orbit, and within the scope outlined by Visions and Voyages. The participants acknowledged that sending a Flagship-class rover to begin these investigations would be expensive and have uncertain scientific payoff and so developed a campaign of missions that began with pathfinding exploration and orbital science.

We discussed three types of missions: an orbiter, "small-sat" landers, and a static lander. The orbiter and static lander would fit within the Discovery Program, and the small-sats could fit within the SIMPLEX program. We detail the results of the second workshop in sections 3.C.1 through 3.C.3

3. Study Results

3.A Major Science Questions and Objectives

We utilized several breakout sessions to determine what are the relevant questions that need to be answered in order to fully describe the climate system and its polar record. Many questions were similar or related, and it became clear that four topics were the most important, high-level aspects of the climate record stored in the PLD.

In their short forms, it was necessary to describe what materials got to the polar regions, the sources of those materials and external forcing required to transport them, how those materials were included in the polar ices, and finally, how those materials were distributed. Here we present the four major questions:

1. What are present and past fluxes of volatiles, dust, and other refractory materials into and out of the polar regions?

2. How do orbital forcing and exchange with other reservoirs, affect those fluxes?

3. What chemical and physical processes form and modify layers?

4. What is the timespan, completeness, and temporal resolution recorded in the PLD?

In shorthand, we refer to these questions as, “**Fluxes**,” “**Forcings**,” “**Layer Processes**,” and “**Record**.”

3.A.1 Fluxes

3.A.1a Observations

Measuring the modern-day flux of material between the polar caps and the atmosphere is a key first step to interpreting the climate record stored in the PLD. It provides the opportunity to link observable climatic processes and their transcription into the polar geologic record. We expect that variation in (i) the isotopic and chemical composition and (ii) total mass of material exchanging between the atmosphere and polar deposits will yield observable signals in the PLD. Therefore, we focus our attention on measuring these quantities and the atmospheric processes (related to global climate and local weather) that govern their flux. To do this, we propose (i) measuring global and regional (km-scale and larger) fluxes; (ii) in situ measurement of fluxing material in the near-surface atmosphere; (iii) in situ surface accumulation; and (iv) in situ measurement of the top few centimeters of ice, which should record information that can be related to the past few decades of martian atmospheric observation.

Four categories of material exchange between the atmosphere and the polar deposits:

- CO_2
- H_2O
- Refractory materials (e.g. dust, salts, volcanic debris, hydrocarbons)
- Trace volatile species

The largest component of the gross annual flux is CO_2, which in condensed form reaches several hundred kg m^{-2} over the PLD. However, orbital observations show that annually, there is no net flux of CO_2 onto the north polar cap and the sign of net CO_2 flux onto the south polar cap is unknown, although the magnitude is probably, on average, <1 kg m^{-2} per martian year (Thomas et al., 2016). Nevertheless, measuring the relative proportion of winter CO_2 laid down through direct deposition vs. snowfall is important because these different modes lead to vastly different thermal, radiative, and structural properties (e.g. Colaprete et al., 2005). This will affect (i) the incorporation of co-deposited material into the polar caps and (ii) the preservation of massive buried CO_2 deposits beneath the south polar cap (Phillips et al., 2011). Additionally, measuring seasonal isotopic variation (e.g. Villanueva et al., 2015) during deposition and sublimation of CO_2 will aid in the interpretation of the isotopic abundances of trapped gas within the PLD and from the deep martian geologic record (e.g. in martian meteorites).

The gross and net annual exchange of H_2O onto either polar cap is unknown, but the net flux is thought to average 0.5 kg m^{-2} over the last few Myr, but is less today or perhaps negative (e.g. Brown et al., 2014; Smith et al., 2016). H_2O forms the bulk of the PLD, with a variable, but low, dust fraction (Grima et al. 2009). The flux of H_2O relative to that of refractory materials under modern climatic conditions is a key measurement for deciphering the climatic meaning of the signal of variable dust fraction stored in the PLD.

In addition to the relative mass fluxes of H_2O and refractory material, the chemical and isotopic composition of this material will yield important information. The chemical composition of the refractory material will provide information about its provenance(s), while potential seasonal isotopic variability in the H_2O flux (e.g. from mass-dependent temperature fractionation or changing source reservoirs) may be used to interpret H_2O isotopic variation recorded in the PLD. Importantly, this isotopic variation may be annual (as is seen on Earth; e.g. Werner et al., 2000) and may provide the smallest resolvable cyclic signal in the PLD. Finally, the flux of trace volatiles incorporated into the polar cap (e.g. trapped in gas bubbles during firn sintering, if present) compared to the ambient atmospheric trace volatile composition will provide insight into deciphering trapped atmospheric gas bubbles in the PLD.

We now present a list of observables that will allow us to deduce the modern material flux at the polar cap-atmosphere interface. This flux matters regardless of whether there is net accumulation or removal of ice from the cap surface because both of these states are recorded in the PLD record (i.e., as either the buildup of ice or the development of a non-volatile lag).

Basic Key Observations:

• Wind speed profile near the surface boundary layer. This observation is important because the near-surface wind speed is determined by nonlinear processes that are impossible to model *a priori*. When observed concurrently with the number density of atmospheric refractory material and H_2O, this is a basic input for calculating regional flux.

• 4-dimensional (altitude, latitude, longitude, and time) number density map of atmospheric dust and H_2O. The ideal minimum resolution for these measurements is a 10-point vertical grid within the first half-scale height (scale hight is ~11km) and half-scale height resolution up to 80 km, at a 4x diurnal cadence, resolved across 12 longitudinal bands, all observed over one full martian year. Isotopic measurements of H_2O (e.g. D/H, $\delta^{18}O$, $\delta^{17}O$) is also important for tracking its provenance. Combined with wind speed, the number density of material is a basic input for calculating regional flux.

• *In situ* surface mass flux of H_2O, refractory material, and CO_2. It is most critical to obtain this measurement at one well-selected location; however, additional measurement locations would allow the determination of regional variability, which can be striking even over ~10 m-scales on Earth (cf. C. Hvidberg presentation at KISS Mars Polar workshop). Characterizing the chemical and isotopic makeup of the surface material is also desirable for determining the provenance of the fluxing material and connecting *in situ* measurements to global measurements.

• Obtaining these measurements concurrently is important for accurately determining fluxes and connecting local deposition to global climatic processes.

Additional desirable observations will improve our understanding of the processes governing deposition, diagenesis, and incorporation of material into the PLD as well as ablation processes and residence time of material that is only transiently incorporated.

Volatile material:

- Cloud density and particle size/shape
- H_2O cloud vs. vapor distribution (in altitude, latitude, longitude, and time)
- Cloud condensation nuclei composition, shape, and size
- Snowfall vs. frost accumulation rates
- Ice and snow crystal structure
- Surface sublimation rate
- Ice grain size, sintering rate and air bubble content
- Ice isotopic abundance
- Pressure and temperature during condensation
- Ice thermal, optical, material properties (e.g. albedo, emissivity, conductivity, density, strength)

Refractory material

- Particle size and shape distribution
- Sublimation lag thickness, permeability to vapor transport, and strength
- Dust lofting rate
- Dust electric charge

3.A.1b Modeling

There are two important considerations regarding how atmospheric models can and will be used in conjunction with observations to quantify the fluxes of non-volatile and volatile material into and out of the polar caps on Mars. The first is that models will be invaluable tools for interpreting and expanding the observations (thus enabling the complete fulfillment of the science goal) and the second is that models require observations for validation purposes.

Interpreting/Expanding Observations:

We expect significant spatial and temporal variations in the surface fluxes of dust and water over the entire cap region due to regional and local-scale circulations and spatial variations in surface properties. While it would be optimal to have a network of a significant number of highly capable meteorological stations placed strategically around the polar regions to measure the spatial variations and temporal evolution of dust and volatiles surface fluxes and transport, it is unlikely to be feasible from a cost perspective. Models will therefore be critical tools for extrapolating information from a small number of stations (possibly just one) to a comprehensive understanding of what is occurring over the entire region. Additionally, unless there are observations from orbit of the global transport of dust and volatiles, concurrent with *in situ* measurements, global-scale climate models will likely be needed to provide this global perspective.

Model Validation:

Before models can be reliably used to extrapolate information gained from one or a few locations to the entire polar cap region, they must be validated with observations. Winds and turbulence in the lower atmosphere control the exchange of volatiles and dust between the surface and atmosphere and transport those materials (in the polar regions and elsewhere). However, to date, these processes have not been comprehensibly or reliably measured on Mars. Near surface wind measurements have been acquired by the Viking Landers, Pathfinder, Phoenix, and Curiosity, but these data sets suffer from calibration issues and other problems.

Winds above ~1.5-2.0 m have never been directly measured on Mars apart from a few entry, descent and landing profiles. Instead, our understanding of the winds throughout the bulk of the atmosphere have come from deriving thermally balanced winds from observed thermal structures and atmospheric models (Navarro et al, 2017). Models require wind observations for validation, particularly near the surface where the thermal wind balance approximation cannot be used. Carefully considered and well-calibrated measurements of near-surfaces winds or wind profiles from the surface will provide this critical model validation. In addition to wind observations, direct observations of the rates of exchange of dust and volatiles between the surface and the atmosphere in the polar regions will provide critical constraints for models. Current state-of-the-art global- and regional-scale models include the physics of dust lifting and removal, and water and CO_2 ice sublimation, deposition, and snowfall. In the absence of measurements of the fluxes from each process, however, it is difficult to know if the models are handling these processes correctly.

3.A.2 Forcings

The climatic state of Mars is driven by changes in the orbital state of the planet and by the presence and longevity of reservoirs. Principally, obliquity variations on ~10^5 yr timescales drive the movement of water ice from mid-latitudes to the pole or equator, and the entire water budget of the planet is potentially affected. Additionally, smaller effects on the pattern of global insolation occur due precession of the argument of perihelion and variations in the eccentricity of Mars' orbit (Laskar et al., 2004). Combined, these three orbital cycles drive much of Mars' climate.

External forcings of Mars' climate include solar winds, cosmic rays, impactors, etc., that act to strip material away from the upper atmosphere or, on smaller scales, implant new materials into the atmosphere. Secular mass loss driven by the solar wind has put Mars into its current, low-pressure state. However, on timescales relevant to the Amazonian period, especially within the last ~300 Myr, atmospheric stripping is not suspected to affect the climate signal in the PLD.

There are also internal climate forcings. The major internal climate driver is the poorly understood dust cycle. Several local and regional dust storms occur repeatedly on annual time scales. The biggest perturbation of the atmosphere by dust is from planet-encircling dust events that cover all longitudes and are so optically thick that visible imagers cannot detect the surface. In these event, atmospheric temperatures increase globally, affecting water vapor distribution and transport. The cause and timing of planet encircling dust events are not understood, but observations record them every few martian years.

Besides the dust cycle, volcanic outgassing must play a role in the variability of atmospheric composition and maybe pressure. The most recent volcanic eruptions are dated at only ~10 Myr, so they are relevant to Amazonian climate, and evidence of eruptions may exist within the PLD.

Reservoirs

It is important to identify the reservoirs of volatiles and refractory materials that can be transported. Water ice is the volatile in greatest quantity at and near the surface of Mars. The two PLD contain more than 2/3 of the known water budget of the planet (although deep aquifers containing comparable amounts of water are suspected to exist). Additionally, mid-latitude glaciers and ice sheets make up another large fraction of the water budget. Smaller known reservoirs include the regolith, through water-binding to minerals or salts, the atmosphere, and pore filling ice. Water may be injected into the atmosphere via volcanoes or comets.

Carbon dioxide is the primary constituent of the martian atmosphere, with a mass of ~2.5 x 10^{16} kg (James and North, 1982). This fluctuates by approximately 1/3 each season as the atmosphere freezes to the winter pole. Additional mass is found at the south polar residual cap (SPRC), a thin deposit of ice (<~10 m) that has minor variations in surface texture and margins (Thomas et al., 2016) and may have been present in some state for several hundred to thousands of years. This makes up only a small portion of the CO_2 budget. The other major reservoir of CO_2 ice is buried beneath the surface of the SPLD, spatially correlated to the SPRC. The volume of this ice is estimated to be as much as 16,500 km^3 (Putzig et al., 2018) and if released to the atmosphere would more than double the surface pressure everywhere. This unit has sequences of deposition (Bierson et al., 2016), suggestive of climate signals (Manning et al., 2018) going back as far as many 10^5 years. Smaller CO_2 reservoirs exist that may play important roles in climate: regolith, minerals, and potentially clathrates.

Finally, dust reservoirs are found across much of the planet. The PLD are nearly pure water ice but may contain ~5-15% atmospheric dust based on dielectric measurements (Grima et al., 2009) and gravity data (Zuber et al., 2007). Other locations on the planet, such as pedestal craters, contain stratified ice and dust as well. Atmospheric dust is visible from ground-based imagery, and many locations on Mars have a fine layer of surface dust reducing contrast in visible and IR bands.

Observables in the PLD

In order to determine the climate cycles and ultimately the forcings that create them, *in situ* measurements of the layers of the PLD must be made. Here we list some known observables and some that are hypothesized to exist.

From orbit, the thickness, albedo, spatial frequency, and dielectric properties of the layers have been measured down to ~1 m resolution for optically observed surface exposures and down to ~8 m for subsurface detection of radar reflectors. We know confidently that some layers have higher albedo and lower dust content and that some layers have higher dust content decreasing their albedo. However, shadows and the presence of seasonal frost affect those measurements, creating uncertainty as to their true nature.

Topographic measurements from stereo imagery provide another way of measuring the layer thickness and spacing, and this technique does a good job of connecting layers at one exposure to layers at another (Becerra 2016). These measurements can be done because the local resistance to erosion permits some layers to erode more slowly, creating steps at resistant layers. We suspect that variable dust to ice ratio is the cause; however, we are presently unable to confidently determine the source of this erosion resistance.

On Earth, layers that were deposited at different times record some fraction of the atmospheric constituents at the time of deposition, including isotopic and chemical signatures. Those materials are beneficial for tracking atmospheric temperature and pressure through time. Mars PLDs are suspected to have variability in their chemical composition depending on when each layer was deposited. If bubbles exist in the PLDs, they may contain samples of past atmospheric gasses.

Dust grain size variability and chemical nature may be measurable. Atmospheric pressure has varied through time (perhaps being double a few 100 ka; (Phillips et al. 2011; Bierson et al. 2016)), and the dust carrying capacity of Mars atmosphere must have varied as well, e.g. higher pressures should sustain larger dust grains as they transport towards the poles. Thus, as dust lifting varies, so too may the dust reservoirs accessible for lifting. If those reservoirs are not identical in chemical composition, then the source of the dust may be identifiable. Along with trapping a record of variability in pressure and dust, each layer will have unique constituents that affect the compaction rate and possibly the final density.

Climate Signal

By measuring the known and potential observables from the surface, we can track the variability at each layer, going backwards in time. If those variables are cyclical in nature, then perhaps we can tie those signals to the periodic nature of seasonal or annual cycles, dust storms, solar cycles, and longer period cycles driven by orbital changes. Tying the forcings to the measurements is the primary method to understanding Mars' climate in the period recorded by the PLD.

3.A.3 Layer Processes

We first discussed five major areas of observables: composition, layer stratigraphy, ice microstructure, atmospheric processes, and surface to subsurface processes. These were subsequently consolidated into three categories: composition, stratigraphy, and current surface processes and meteorology.

Composition was identified as the top priority because it is the primary way to deduce processes that form and modify layers, identify sources of materials that make the layers, infer surface-atmosphere interactions, and preserve climatic events. The relative abundances of the most abundant constituents (water ice, carbon dioxide ice, salts, and dust) will be key for study related to these topics. Identifying trace quantities of other materials (organics, isotopes, perchlorate, clathrate) and identifying composition at multiple spots (if landed) or better vertical resolution than currently available (if in orbit) are also important. The physical characteristics of materials in the layers (e.g. grain size distribution, density) will also provide information about their origin and diagenesis. These observations will require an instrument capable of identifying ices, dust and trace constituents. Image acquisition at small-scale excavations or existing exposures can probe near-surface stratigraphy and composition.

Stratigraphy places composition in context and links the historical record to current processes and evolution over time. We need to characterize the stratigraphy at a scale below the resolution available from orbit (1-10 m), but also relate it to the broader context of the stratigraphy identifiable from orbit. Imaging from a surface perspective as well as sounding techniques (e.g. ground-penetrating radar) are desirable. Elucidating the evolution of the PLD requires understanding changes in deposition rates by observing bedding geometry, thickness and unconformities to understand how deposition has changed through time.

The study of current surface processes and meteorology illuminates how layers are forming or eroding today and links current processes to historical processes preserved in the stratigraphy. This requires *in situ* observation of the ablation and/or accumulation of dust and ice, saltation and surface transport of materials, and measurements of wind, insolation, humidity, and albedo.

Layer processes link directly to four of the five key Mars polar science questions identified at the 6th international conference on Mars polar science and exploration, as summarized by Smith et al. (2018). In particular, they relate to questions about the polar atmosphere (question 1), Perennial surface ices (question 2), the polar record of the past climate (question 3), and the present-day polar surface activity (question 5).

The three priority areas we identify (composition, stratigraphy, and current surface processes) are directly linked to many observations that could be made by the Next Mars Orbiter, whose instrument complement was recently studied by MEPAG (NEX-SAG Report, 2015). That report identified new science that could be done by an orbiter to:

1. *"Map and quantify shallow ground ice deposits across Mars together with shallow layering of*

water and CO2 ices at the poles to better understand the global water inventory and atmospheric exchange today, and how ground ice records climate change on geologically younger Mars (e.g., over obliquity variation cycles)."

2. "Measure winds and characterize transport and other dynamic processes to understand current climate, water, and dust cycles, with extrapolation to past climates".

Included in the NEX-SAG report were high-level, proof-of-concept measurement techniques mature enough for development of an orbiter for launch in 2022, including:

- Visible imaging of HiRISE-class (30 cm/pixel) or better (~10-15 cm/pixel)
- Polarimetric radar imaging with penetration depth of a few (<10) meters and spatial resolution of ~15 m/pixel to detect ices; a radar sounding mode would aid characterization of the overburden mantling subsurface ice layers
- Short-wave IR mapping with a spatial resolution of ~6 m/pixel with sufficient spectral resolution to detect key primary and secondary minerals, salts, and ices
- Long-wave atmospheric sounding for wind, temperature, & water-vapor profiles
- Thermal IR sounding for aerosol profiles
- Multi-band thermal IR mapping of thermophysical surface properties (e.g., ice overburden and thermal inertia) and surface composition
- Global, km-scale, wide-angle imaging to monitor weather, dust storms, and surface frosts

Landed mission concepts and instruments that can address these priority areas were considered as part of the Mars Polar Climate concept study that was prepared as part of the 2013 Decadal Survey (NASA Mission Concept Study, 2010). Measurement technologies that can address composition, stratigraphy, and current processes from landed or rover platforms include concepts that have already flown on landed missions or are in preparation, such as:

- Scene and Distant targets
    - Mast Imagers (stratigraphy, unconformity, bedding geometry)
    - Mast Spectroscopy (LIBS or Infrared) (composition of ice and non-ice constituents)
    - Environmental monitoring (pressure, temperature, wind vectors, humidity, ultraviolet flux)
    - Atmospheric sounding (FTIR, Lidar, clouds, dust, surface-atmosphere exchange)
    - Surface heat flow (thermal metamorphism)
    - Ground penetrating radar (layer properties of the upper 10s of meters)
    - Neutron or gamma ray detectors (near-surface composition)
- Sample scale targets
    - Drill, RAT or corers (access to subsurface stratigraphy)
    - Drill Imagers (down-hole imaging of layer properties)
    - High-resolution Imagery (imaging of extracted samples)
    - Infrared or Raman Spectroscopy (down-hole or sample composition)
    - Tunable laser or mass spectroscopy (sample composition of trace components and isotopes D/H, $C^{12,13,14}$)

3.A.4 Record

In order to address the science question "What is the timespan, completeness, and temporal resolution recorded in the PLD?" we identified three time (and size) scales that need to be addressed.

The largest physical scale (and by extension temporal scale) is characterizing the stratigraphy of the PLDs as a whole. The geologic relationships between the four packets of radar layers and the basal unit characterized by (Tanaka et al., 2008; Phillips et al., 2008; Tanaka et al., 2012) would be better constrained by radiometric age dates and/or exposure age dates of lithics contained in the cavi and basal units. Additionally, SHARAD data has been combined to make a 3 dimensional map of the NPLD (Foss et al., 2017) including circular depressions that have been interpreted to be craters (Putzig et al., 2018). Using the size-frequency distribution (SFD) of these circular depressions would give additional information about the expected ~5 Myr history of the NPLD from ice stability and climate modeling (Jakosky et al., 1995; Laskar et al., 2002; Levrard et al., 2007). Whereas this 3D modeling has been completed for the SPLD, internal volumetric backscatter or "fog" inhibits comparing the climate record that could be preserved at both PLDs (Whitten and Campbell, 2018). These constraints would characterize the timespan and the largest temporal resolution contained within the PLDs.

The intermediate physical scale we identified was the trough exposure scale, or on the order of ~100s of meters vertical scale. Identifying unconformities is a priority for understanding the completeness of the record contained in the PLDs because hiatuses in accumulation or periods of ablation could alter or fail to preserve some of the record. One way of doing this is looking for layers with high concentrations lithic material in the stratigraphy exposed within troughs, which may be sublimation lags. The bulk dust content of the NPLD is ~5% (Grima et al., 2009) and the SPLD ~15% (Zuber et al., 2007) so sublimation-lag-dominated layers, if present, do not dominate the contents of the PLDs and are likely quite thin. However, visible/near-infrared spectral investigations of the layers suggest that lithics and salts may be present, and variability in their concentration may help understand the relative impacts of hiatuses in the record. Thus, being able to fully characterize the physical (e.g. ice crystal size, air bubble presence and/or concentration, density) and chemical (e.g., lithic mineralogy, dust concentration, salt concentration, gas/ice isotopic composition, gas/ice elemental composition) properties of these layers will enable the search for patterns within them that could link the larger structure to possible annual layers (or packets of annual layers) near the surface.

Finally, it is important to study the current surface and upper meter of the PLDs at the sub-mater scale. Understanding the fine-scale structures in the near-surface of the PLD is key to interpreting the deeper record. Understanding what constitutes a layer and linking layers to observed near-surface processes is critical for identifying the finest spatial (and therefore temporal) resolution of layers recorded in the PLD, and ultimately assigning absulate ages to the PLD climate record.

Whether an annual layer is preserved in the uppermost region (decimeters to meters scale) of the PLDs is not known. Additionally, based on apparently conflicting lines of evidence about the current mass balance of the NPLD (Kieffer, 1990; Langevin et al., 2005; Chamberlain and Boynton, 2007), it is unclear if the NPLD is currently adding annual layers or losing part of a past climate record. Additionally, little is known about how the PLD material densifies with depth and whether any air bubbles from previous martian climates could be captured within the ice, similar to terrestrial examples (e.g. Svennson et al., 2005). A better model for ice evolution will allow us to constrain the past conditions that near-surface ice has experienced (e.g. is the current surface being exhumed or undergoing preservation by compressing a fluffier frost layer?). Additionally, physical and chemical measurements of the near surface ice (e.g. dust content, optical properties, electrical conductivity, lithic/gas/ice composition) could lead to the detection and evaluation of recurring, and possibly annual, patterns that could be linked to the timescale of the larger, trough-scale exposures.

We identified several key measurements that would address the above areas of needed knowledge and ranked them according to priority.

• Our top priority was to obtain an absolute age through cosmogenic/radiogenic nuclei abundance for any location within the PLD. This will allow researchers to put an independent age constraint on at least one of the layers, and with less uncertainty than absolute crater ages (e.g. Herkenhoff and Plaut, 2000; Koutnik et al., 2002; Banks et al., 2010; Landis et al., 2016), as radiometric/cosmogenic dating is independent of crater production models. There are a variety of radiosotopic systems and methods available for age determination on the Earth (e.g. ^{14}C, ^{10}Be, K-Ar, ^{36}Cl, ^{3}He, ^{36}Ar, Ne). Optically stimulated luminescence techniques are an additional technique available for age determination. These methods require the presence and identification of a datable lithic layer (e.g., impact or volcanic sediments). The transferability of these methods to Mars needs further study.

• Intermediate priority was given to the search for patterns in vertical distribution of impurity fraction and chemistry (iron, silica, aluminum, sulfur and chlorine) to match orbital history on the 100s of m depth/trough scale. The study of impurities could be carried out using optical microscopy and context imaging combined with a compositional technique like alpha particle x-ray spectroscopy (APXS), laser-induced breakdown spectroscopy (LIBS), x-ray fluorescence (XRF), and/or visible/near-infrared spectroscopy. Annual layers are estimated to be on the microns to ~mm scale (e.g. Laskar et al., 2002; Hvidberg et al., 2012) and obtaining that vertical resolution would assist in determining the smallest time resolution recorded in the PLD layers.

• Intermediate priority was also given to the measurement of the crater size-frequency distribution (SFD) with depth to determine relative ages from vertical crater distribution. The vertical crater SFD would require higher resolution, and therefore higher power, radar than SHARAD to detect craters below the 7 km detected in initial surveys (Putzig et al., 2018). While absolute age results would still be crater production-function dependent, quantifying the crater size-frequency distribution with depth places relative age constraints on the PLD. Additionally, tying the timescales presented in the vertical crater distribution to a fixed radiometric or cosmogenic age from our top measurement priority would significantly improve the interpretation of this result.

• We also identified three supporting measurements that were key in answering our central science question. The first is determining the completeness of the PLD with a catalog of unconformities throughout the stack. To map unconformities, we considered again higher power (and therefore higher resolution) radar as well as a network of seismic stations that could map the distribution of layer packets and gaps. The second is measuring current atmospheric conditions and surface effects, ideally through a combination of surface microscopy and a network of meteorological stations. Third is grain size measurement with depth in the first few meters of the surface. This would require microscopic and spectroscopic tools to drop down a borehole a few meters into the surface.

3.A.5 Age Dating the NPLD

In order to tie physical layers seen in radar to obliquity and climate cycles on Mars, age constraints must be placed on layered materials. Formation and exposure ages are obtained on Earth (and Mars, e.g. Farley et al. 2014) using radiogenic and cosmogenic nuclides. Briefly, cosmogenic nuclides are produced through any interaction of primary or secondary cosmic radiation with matter containing a range of target elements. Stable nuclides build up over time as a surface is exposed to cosmic rays. Radiogenic nuclides are daughter products of radioactive decay and also build up on surfaces to the point of saturation, which refers to the state when the rate of production equals the rate of decay. When a surface is buried, the accumulation of cosmogenic and radiogenic nuclides slows down or stops entirely, depending on the nuclide (Figure 1.) The cosmogenic stable nuclides remain, while the radiogenic nuclides decay into stable daughters. The production rate of cosmogenic nuclides on Mars is estimated from meteorites, and can be used, along with a measurement of the abundance of these nuclides in a layer, to determine how long the material in the layer sat on the surface. The burial age of the material can then be determined by the difference between the abundance of cosmogenic nuclides in currently exposed surface materials vs. buried materials.

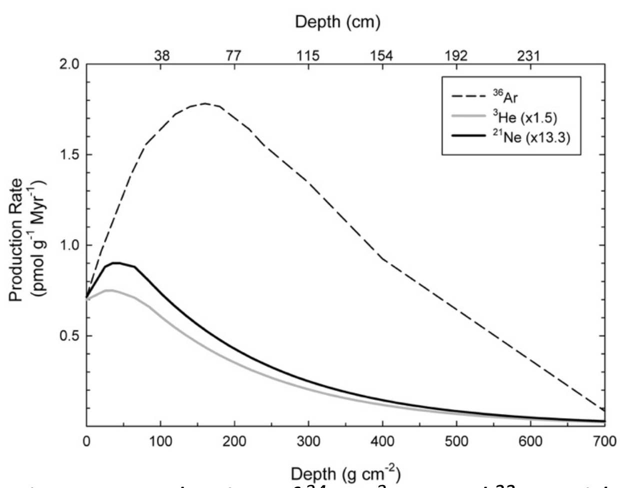


Figure 1 Production of ^{34} Ar, ^{3}He, and ^{22}Ne with depth on Mars, from Farley et al., 2014

Cosmogenic and radiogenic dating techniques are widely used in studies of ice cores and glacial geomorphology on Earth, with ^{10}Be (half-life ~1.5 My), ^{26}Al (half-life ~700 ky), and ^{14}C (half-life ~5700 y) as the most frequently used dating systems (e.g., Fabel et al, 2002; Bond et al., 1993; Rinterknecht et al., 2006). For the most part, age dating is done on lithic material and volcanic ash entrained in ice, although in some cases trapped gases are analyzed (e.g., Buizert et al., 2014) with state-of-the-art noble gas mass spectrometers. However, for this technique, very large masses of ice (100s of kg) are required to obtain sufficient material to analyze with high sensitivity, preclude doing this on Mars.

Cosmogenic and radiometric dating on Mars presents significant analytical challenges due to the amount of material necessary for measurement and the necessity (in most techniques) to have a robust mass estimate of material. A successful application of radiometric (K-Ar) and exposure age dating on Mars using cosmogenic ^{21}Ne, ^{3}He, and ^{38}Ar have been performed on Gale Crater mudstone (Farley et al., 2014) using the SAM instrument on MSL. However, this work was done on martian regolith, where rocks with high concentrations of target elements (e.g., Mg, Ca, Al) ensure the presence of measurable abundances of cosmogenic nuclides.

Because the NPLD are mostly ice, achieving meaningful ages for the NPLD material hinges on the presence of datable lithic material in the form of dust, volcanic ash, or impact ejecta. The young age of the NPLD (~5x10^{6} years old) also drives the requirement for extremely high precision measurements in order to achieve meaningful ages, with minimum age resolution on the order of 10^4-10^5 years. For comparison, the exposure age measurements achieved by SAM were 78 ± 30 million years (Farley et al., 2014), suggesting an improvement in precision of at least 2 orders of magnitude would be required for meaningful measurements of the NPLD.

A mission to age-date the NPLD would require a highly selective and sensitive mass spectrometer similar in size, mass, and power to the SAM instrument on MSL. A range of mass spectrometry techniques to optimize exposure age dating using cosmogenic nuclides are currently in development to address the need for absolute age dating in planetary science. These techniques represent improvements in sensitivity, resolution, and selectivity over mass spectrometers currently used in planetary exploration. One promising technique in development is resonance ionization mass spectrometry (RIMS), which uses a laser or ion beam to remove neutral atoms from solids, then uses tuned lasers to excite electrons of a specific element and ionize it for measurement by mass spectrometer. This technique has been developed for the Rb-Sr geochronometer (Anderson et al. 2012; 2015) but could be applied to cosmogenic nuclides as well. In addition, recent developments using isotope dilution remove the need for obtaining a mass estimate, which should significantly reduce the magnitude of error (Farley et al., 2013). A precursor mission to establish the presence and abundance of datable lithic material in the top of the NPLD could inform efforts to refine these and other age dating techniques (e.g., Cohen et al., 2014) for application to the NPLD.

3.B Key Properties and Measurements

Based on the discussions within the breakout sessions, our group converged on an agenda for measurements that can be made with existing and foreseeable technology to address our primary and secondary questions. This section describes those measurements and the requirements associated with them.

3.B.1 Requirements for Measurements of Fluxes in the Polar Regions

An understanding of the layering of the polar deposits and its relation to past climates requires an understanding of the processes that control the accumulation and erosion of the polar caps in the current climate. For this it is necessary to quantify the deposition of dust and volatiles on the polar cap as well as the inflow and outflow of dust, water ice, and water vapor to and from the polar region. This is summarized as flux measurements. Flux measurements will have to be performed near the surface in order to quantify fluxes that are directly relevant to deposition and ablation processes. These measurements will likely have to be performed from surface stations and would have to be supplemented by orbital measurements (global, vertical profiles of dust, water vapor, and water ice clouds) in order to connect the surface measurements with the processes that govern the current global climate.

Measurement requirements

To assess polar fluxes, atmospheric measurements at and near the surface should include, wind speed and direction, temperature, pressure, and humidity. If these measurements are performed with a sufficient accuracy and repetition rate, they will be able to resolve atmospheric fluxes relevant to the current climate. Of critical importance is to measure the transport by turbulent eddies in combination with humidity and particle measurements. To achieve this, the requirement on a wind measurement would be a precision of a few cm/s in three directions at a temporal resolution of ~20 Hz at least once per hour. Surface pressure measurements should provide long-term stability of 0.1 mbar with a precision of 0.02 mbar to be fruitful. The temperature measurements should fulfill a 0.5 K accuracy requirement. The combination of these measurements would allow the characterization of heat and momentum fluxes in the lowermost polar atmosphere.

Humidity will provide information on water vapor content and transport in the lowermost atmosphere. The accuracy requirement for this measurement is of order a few parts per million (ppm). Humidity measurements with a high temporal resolution (~20 Hz) in combination with wind measurements of the same resolution would allow the determination of water vapor transport through turbulent eddies. Alternatively, water vapor transport could be derived from similar frequency measurements of the water vapor gradient at 2-3 heights measured from a tall tower, the height of which would have to be determined.

In addition to wind and water vapor, fluxes of dust and condensates will have to be characterized. CO_2 condensates are hard to measure in-situ and are only permanent on parts of the southern polar cap, so the considerations here are restricted to water ice condensates. In order to obtain fluxes in the atmosphere, dust and water ice particles should be counted individually. Instrumentation should be sensitive to micron-sized particles and able to discriminate between dust and water ice. Together with hourly wind measurements, particulate measurements would enable the determination of dust and water ice particle transport through turbulent eddies. An additional or alternative measurement would be the direct accumulation of dust and water ice on the surface (or robotic device). This would provide mass flux in one direction, perhaps as great a 0.5 to 1 mm per year. Microgram sensitivity is required. In addition, it should be possible to discriminate between dust and water ice accumulation, perhaps by sorting or sublimating the ice. Furthermore, measurements of optical surface properties could supplement the characterization of environmental conditions and the interpretation of deposition and erosion measurements.

In order to give a comprehensive picture of fluxes in the polar region, 5-6 stations with the aforementioned measurement capabilities would be needed. Flux variations are expected to primarily vary with latitude and elevation so that stations placed on the polar cap along one longitude at various latitudes would be able to capture the dependence on latitude and elevation.

Potential technologies

Measurements of wind speed and direction would be best acquired by a sonic anemometer. It can be set up to measure in three dimensions and would fulfill the measurement precision and temporal resolution requirements (Banfield and Dissly, 2005). A sonic anemometer could also measure temperature to an accuracy of ~0.2 K. An alternative technology could be a wind lidar, which could provide vertical profiles of wind and direction. While they are frequently used in ground-based applications on Earth, no wind lidar has been deployed on Mars yet. A hot wire or hot film anemometer as deployed on Mars Pathfinder or Mars Science Laboratory has a measurement sensitivity of order 1 m/s at 1 Hz. While still useful, it would not be able to resolve turbulent eddies. Surface pressure can be measured by magnetic reluctance diaphragm sensors (Hess et al., 1977) or capacitive sensors (Gómez-Elvira et al., 2012), which have extensive heritage from Viking, Mars Pathfinder, Phoenix and Mars Science Laboratory.

For humidity measurements a laser hygrometer based on Tunable Diode Laser technology (TDL) provides high sensitivity at high repetition rates (Webster et al., 2004). Such an instrument has been deployed on the Mars Science Laboratory.

Measurements of dust and water ice mass flux could be achieved by aerosol optical detectors or nephelometers. Nephelometers measure particle densities that pass through a light beam and a light detector (e.g. a laser emitter and a photocell receiver) either in transmission or scattering geometry. They could also measure particle size distributions and optical properties. Deposition measurements could be made by a microbalance device. These devices work with thermally stabilized piezoelectric transducers, whose frequency is proportional to the mass deposited on the sensor. They were proposed for the MEDUSA surface instrumentation package (Ventura et al., 2011). For the application of water ice measurements it would have to be possible to heat microbalance in order to sublime deposited volatiles, yielding the difference between water ice and dust deposition. Measurement requirements and potential technologies for in-situ measurements are summarized in Table 3.1.

Table 3.1: *Measurement requirements and potential technologies for in-situ flux measurements.*

Measurement	Sensitivity requirement	Measurement frequency	Number of stations	Potential technology
Wind (near surface)	few cm/s	20 Hz	5-6	Sonic anemometer
Water vapor/ humidity	few ppm	20 Hz	5-6	Tunable Laser Spectrometer
Dust/water ice flux	individual particles, μm radius	< 1 Hz	5-6	Nephelometer
Dust/water ice accumulation	< 1 μg	daily	5-6	Micro-balance (evaporation capabilities)

Measurements from orbital assets could supplement or replace some of the aforementioned in-situ measurements. Global measurements of vertical profiles of dust, water vapor, and water ice clouds would be necessary to connect the surface measurements with the processes that govern the current global climate. These kinds of measurements have been provided, for example, by the Mars Climate Sounder (Kleinböhl et al., 2009, 2017, McCleese et al. 2010) on Mars Reconnaissance Orbiter. Contributions to deposition and erosion processes could possibly be made using lidar or interferometric synthetic aperture radar (INSAR). However, it is not certain that the accuracy of such instrumentation from orbit would be sufficient to directly measure deposition or erosion rates over short time scales. Finally, it may be possible to support deposition and erosion studies by bringing out an artificial surface or a dye on a defined area of the polar cap. Measuring changes in the optical properties of the dyed surface over the season from a surface camera or from orbit could provide information on dust or ice deposition as well as erosion processes. Care must be taken with the interpretation of such measurements as the dyed surface will likely change the surface roughness and radiative properties in comparison to an unmodified surface.

3.B.2 Requirements for Measurements of Layer Properties in the Polar Regions

The polar layered deposits (PLD) are expected to consist meteoric ice. Formation of these deposits begins with the accumulation and densification of atmospheric ice as snow into firn or direct deposition that eventually fills pores by compaction and diffusion.

On Earth, in the top 10-20 meters of firn, the gas in pores exchanges with the atmosphere through convection. Below this depth, porosity decreases and gas transport occurs via diffusion. At a depth of approximately 50 – 100 m, sintering of ice crystals traps the gas in bubbles and the firn is no longer permeable (Sowers, 1992; Gow, 1969). The specific close-off depth (~75m on Earth) depends on accumulation rate and gravity. Meteoric ice is characterized by the impurities present in the environment during its formation. Variations in the concentration of isotopes and ions with depth are used as a dating mechanism and for the study of paleoclimate.

On Mars, it is unknown what fraction of annual accumulation occurs via snowfall vs direct surface deposition. Observations by the near-polar Phoenix lander showed both water ice crystals and surface frosts (Whiteway et al. 2009). Models of PLD accumulation and thermal inertia suggest that the surface layer is dense, implying that densification may be rapid and the firn only a few cm thick (Arthern et al 2000); however, direct observations are lacking.

We observe discrete layers of particulate impurities (Fishbaugh 2010a; 2010b; Becerra 2016) (e.g. dust, and possibly volcanic ash) within an ice matrix that characterize specific layers. These will reflect periodic depositional events or may be lag deposits from episodes of ice ablation, associated with climate drivers. Depositional events of particulates may reflect stochastic processes such as global dust storms or ash fall from volcanic activity. The thickness and stratigraphy of the these alternating layers can inform us about martian climate over the period sampled by drilling, and perhaps allow us to infer cyclical events in past climate.

In the context of layer thickness, frequency, stratigraphy, and structural relationships of the martian polar layered deposits it is paramount to gather measurements at various locations and depths. Since the size of the smallest layer (or for that matter, what defines a layer) is unknown, high-resolution measurements are needed. We envision a combination of two methods to do so. Both would offer an unprecedented look at the structure, stratigraphy, and layer thickness and properties. The first would involve sampling of layers using multiple methods along the gently sloping trough walls at various locations. This could be gathered via a mobile platform that covers many km of transect and accesses hundreds of layers.

The second method is using boreholes drilled within the PLDs. A 1-m drill (e.g. Honeybee Robotics Icebreaker Drill) would offer rock/ice competency (in MPa) and density measurements within 20% error. Ideally, these measurements would be taken continuously but discrete measurements at 10 cm intervals would be sufficient. Once a borehole is drilled, an optical borehole imager (e.g. Mount Sopris Instruments QL40-OBI-2G Optical Televiewer) could be lowered into the borehole in order to identify and count layers, and identify depths of interest for further investigation. An optical logger captures 360° images of the borehole wall and can detect discrete layers (i.e. of particulates in ice), layer thickness and dip. Vertical resolution is a function of the device and the logging speed. We expect to need < 1mm resolution in order to discern the thinnest layers within the ice associated with approximately annual deposition. Once areas of interest have been identified, a microscopic imager with a resolution of about 30 µm / pixel would record high-resolution imagery. Resistivity probes lowered within a borehole could be used to help correlate ground-penetrating radar (GPR) data with visible layers in the subsurface. Multiple boreholes also offer the chance for cross-borehole tomography (seismic imaging method).

Surface-based non-destructive geophysical techniques could be deployed as well, albeit with coarser resolution. The top layers of the PLDs are not resolved by current sounding instruments SHARAD or MARSIS. In order to resolve these shallow features, a higher-frequency GPR, either in orbit or on a rover/lander, would be useful especially one that offers >100 m penetration depth with 10 cm range resolution. Similarly, an advanced active source seismic system could resolve the layers and offer varying depth penetration depending on the separation of source and receiver, however, this method is restricted to a rover/lander system.

In Earth's Polar Regions, research concerning the discrete layers of particulate impurities is done by collecting ice cores, returning them to a laboratory, and subjecting samples to a variety of analyses, such as: thin section stereology (for ice grain size and crystal orientation); electrical conductivity measurement (ECM) for identifying variations in acidity (that on Earth reflect forest fires, a seasonal marker in some locations); meltwater analysis for dust concentration, ion and isotope chemistry; and X-ray micro computed tomography (microCT).

Drilling and withdrawing cores is straightforward on Earth, where humans intervene at every state. Handling and sampling them on a Mars robotic lander would be significantly more difficult. Besides bringing a core to a lander deck, it is foreseeable that instruments cold be designed to fit in a bore hole, such as an ECM or an optical borehole logger. Each has limitations

MicroCT can examine layering by particle size and shape, and potentially by relative atomic weight. MicroCT provides nondestructive three-dimensional visualization and characterization of the internal features of multiphase materials with spatial resolution down to several microns. It has been used extensively in the study of depositional processes in sedimentary rock (e.g. Falvard and Paris, 2017) and more recently in ice (Obbard et al., 2009; Iverson et al., 2017).

In ice, microCT can measure micron-scale layer stratigraphy, particle size, shape, volume concentration with respect to depth, pore size, shape and distribution with respect to depth, and potentially discrimination of salts from Fe-rich sediments. The use of microCT analysis to differentiate ash layers from specific eruptions has been demonstrated in the West Antarctic Ice Sheet (WAIS) core (Iverson et al., 2017, in review). Sample handling would be difficult, so we seek a microCT system that could analyze a free standing core left by a coring drill.

The expected polycrystalline nature of PLD ice may contain useful information. On Earth, crystal orientation (fabric) and size and shape (texture) provide information about stress, flow and temperature in glaciers and are critical for understanding its mechanical behavior and modeling its movement.

Crystals, also called grains, are initially small, but grow with time (grain area increases linearly with age), an effect of the tendency of the system to reduce free energy by minimizing grain boundary area. Terrestrial models of this growth process and how it is limited by impurities compare well with observations (e.g. Durand et al., 2006). Past models of the martian PLD (Kieffer, 1990) can relate ice grain size vs depth in the uppermost meters to surface accumulation rate. Thus a measurement of grain size as a function of depth has utility at the PLD. Grain size measurement techniques need to be effective from 10 to 1000 microns in order to conduct this investigation. The standard approach to this measurement would be to observe thin sections from ice cores under polarized light. Within a borehole however, this quantity is difficult to measure. Sublimation occurs preferentially along grain boundaries (Obbard et al., 2006), so re-imaging the borehole at high resolutions 10s of days after it is created may allow grain boundaries to be visible. Alternatively, if the ice remains granular and porous within the uppermost meters then near-IR spectroscopy can be used to infer grain sizes. It is unlikely that this investigation could be conducted by traversing a trough of exposed layers because they are all exposed in the current epoch and experience the same temperature variations.

The ice phase expected under martian surface conditions is the same as terrestrial surface i.e. ice Ih. This hexagonal arrangement of water molecules in parallel planes means that plastic deformation is much easier perpendicular to the c-axis than other directions. Ice grains in high-strain environments tend to rotate until their c-axis points perpendicular to the direction of strain after which they can be readily deformed. Unstrained meteoric ice should not show preferred alignment of ice crystal basal planes. Thus an investigation into basal plane orientation could provide a constraint on past ice flow within the PLD. Such an investigation would have a low chance of success. The low temperatures and gravity mean that these near-surface layers are unlikely to have been affected by flow. Stratigraphic studies (Karlsson et al. 2011) have shown that ice flow has likely been minimal over most of the PLD although models predict high flow rates over rare locations where slopes are very high (Sori et al. 2016). Searching for preferred grain alignments in traverses of trough walls is potentially more promising as moderate surface slopes are nearby and older ice layers have been more deeply buried and so have experienced higher stresses and temperatures. However, the technical limitations described in the grain size investigation above are even more severe in identifying preferred grain alignments. Although it would be a useful metric to measure, grain alignment seems technically difficult at this time.

3.B.3 Requirements for Measurements of Composition in the Polar Regions

The climatic record of the polar layered deposits is stored as variability in both the physical and chemical nature of the ice and entrained sediments. In this section, we discuss the measurements that could be made to constrain the compositional and electrical properties of the PLD and outline possible instrument payload solutions and investigation strategies.

Required Measurements

The volatile component of the polar layered deposits is inferred to be composed largely of water ice, with other atmospheric gases trapped during deposition in the form of micro-scale bubbles. It is unknown whether or not CO_2 ice is present within the PLD, as clathrates, but it has not been ruled out as a possibility. The composition of the ices can be constrained both based on their bulk abundance (e.g., H_2O vs. CO_2 fractions at 1 wt% or better) and based on isotopic ratios. Determining the isotopic composition of new ice forming at the poles and the isotopic record within the PLD would place important constraints on source reservoirs and modern fractionation processes. Isotopic measurements should include D/H to a precision of 100/mil over the range of 100-9000 mil, $^{18}O/^{16}O$ at a precision of 3/mil, and $^{13}C/^{12}C$ at a precision of 5/mil. These measurements could be directly compared to isotopic measurements of the modern upper atmosphere by MAVEN or ancient hydrated minerals in Gale crater sediments and martian meteorites. These can inform models of long term atmospheric escape.

Like in ice cores on Earth, we hypothesize that the PLD contains relict gases, trapped during deposition as bubbles, and possibly as clathrates. These gases provide a record of the composition of the atmosphere under recent climatic conditions, which could be assessed based on abundances of major (CO_2, N2, Ar, O_2, CO at a precision of 0.1% or greater) and minor (H_2O, NO, Ne, HDO, Kr, Xe at a precision of 10-100 ppb) gases measured by Viking, as well as other important volatile species like S, Cl, and CH_4. Bubble size and density would also be an important indicator of ice compaction and maturity.

Multiple types of non-ice solids have been identified within the PLD based on orbital spectroscopy, including martian surface/atmospheric dust (composed of an assemblage of phases including nanophase ferric oxides, primary minerals, and S/Cl-rich salts; Morris et al., 2004; Yen et al., Hamilton et al., 2005; Yen et al., 2005), perchlorate and sulfate salts (Horgan et al., 2009; Calvin et al., 2009; Masse et al., 2010, 2012), and primary mafic sediments (e.g., pyroxene and glass; Horgan & Bell, 2012; Horgan et al., 2014). Organics may also be present in the PLD from meteoritic inputs. The vertical distribution of these “impurities” within the PLD is not well constrained, but they are probably present both in distinct sedimentary layers (e.g., aeolian layers, past sublimation lags, ash layers, and impact ejecta) and as a volumetric component incorporated during seasonal deposition. The composition, grain size, and distribution of these non-ice solids are all important measurements for constraining the history of the PLD and links to atmospheric processes.

Determining the mineralogy (precision 0.1 wt%) and elemental composition (e.g., Si, Fe, Cl, S at 0.1 wt%) of soluble impurities like salts would help constrain modern and recent atmospheric chemistry and the degree of rock/water interactions on the surface. Similarly, determining the composition and abundance (sensitivity of ppm to ppb) of organics would place important constraints on modern meteoritic inputs on Mars. Determining the mineralogy (precision 1wt%) and grain size (for ~1 µm particles and larger) of insoluble impurities like primary minerals and glasses would help constrain ejecta and volcanic inputs to the PLD, and would help to determine whether to not these materials are in sufficient quantity that they could be used to determine the age of individual layers. In the case of volcanic ash or impact ejecta with a melt component, crystallization age would constrain the age of that layer of the PLD. In principle, the deposition age for a broader range of sediments could be determined based on time since exposure to cosmic rays or visible light as discussed in Section 3.A.5.

Determining bulk properties of the PLD including conductivity and permittivity would also assist in constraining the distribution of ices, bubbles, and lithics through the stack, and would provide key inputs for more accurate analyses of existing RADAR data.

Measurement Strategies

Composition is primarily useful as a proxy for past climate and other geologic influences on the PLD, and thus is most useful when extracted as a semi-continuous stratigraphic record that can be correlated with climate models. To tie variability in composition to climatic cycles, a detailed vertical sampling of the composition of the PLD would be required, most likely at a vertical resolution on the order of 0.5 mm. Landing site selection should account for regions with significant dust cover and ongoing modification of the ice surface (e.g., Smith & Holt, 2010). To interrogate a sufficiently long temporal record, access to hundreds of meters of vertical stratigraphy may be required.

On Earth, ice stratigraphies are typically analyzed as intact cores after they are brought to the surface. On Mars, this type of analysis is probably infeasible, so analysis could take place (1) within the borehole, via direct sampling, remote sensing, or contact measurements of the borehole wall, or (2) on the surface platform on drill cuttings (e.g. crushed and/or melted ice extracted at intervals by the drill). Remote sensing and/or contact measurements within the borehole would require communication with instruments on deck or instruments that fit in the borehole. Direct sampling of ice for detailed chemical analyses could also occur along the borehole walls, either as part of the drill itself or via a separate probe inserted after drilling is complete. Care must be taken in sample preparation, as crushing or melting may release trapped gases and melting may place them in solution. Melting may also be problematic in the presence of sediments.

Possible Payload Elements

Ice composition and ice grain size as well as the mineralogy of impurities could all be assessed rapidly via short-wave infrared reflectance spectroscopy (SWIR; 1.0-2.6 microns), which has been shown via orbital remote sensing to be highly sensitive to key phases in the PLD (references above) and has been successfully miniaturized for a variety of spaceborne applications. Alternatively, laser-induced scattering via Raman spectroscopy can also determine mineralogy and ice composition, and Raman instruments like the Mars 2020 Scanning Habitable Environments with Raman & Luminescence for Organics & Chemicals (SHERLOC) and SuperCam spectrometers will be flown on multiple in situ missions to Mars over the next few years. In principle, either reflectance or Raman spectroscopy could be implemented within a borehole using fiber optic cables.

Multiple missions have successfully interrogated the bulk chemistry of the surface of Mars, using one of several common types of instruments. Bulk chemistry of borehole walls or other solid samples could be assessed via X-ray fluorescence (XRF), as implemented in the Planetary Instrument for X-ray Lithochemistry (PIXL) instrument on Mars 2020, via alpha particle X-ray spectroscopy (APXS), as implemented on multiple Mars rovers, or via laser-induced breakdown spectroscopy (LIBS), as implemented in the MSL ChemCam and Mars 2020 SuperCam instruments. LIBS has been implemented with long fiber optics cables and may be more applicable to small diameter boreholes.

Determining the composition of trapped gases requires another set of techniques. Tunable laser spectroscopy (TLS), as implemented on the Phoenix lander, could provide information on the bulk and isotopic composition of major gases. Any additional analysis beyond this would require a mass spectrometer, perhaps similar to Neutral Gas and Ion Mass Spectrometer (NGIMS) on MAVEN. A mass spectrometer that also included pyrolysis or laser ablation, such as SAM on MSL, could be further applied to non-ice solids to detect and characterize organics, or potentially utilized for exposure age dating of sediments via cosmogenic nuclides. All of these approaches would require transport of meltwaters, trapped gases, and potentially trapped sediments up through the borehole to the surface platform. Alternatively, burial ages could potentially be extracted within the borehole via a much simpler technique like optically stimulated luminescence (OSL), although this technique has low heritage for planetary missions.

3.C Mission Concepts and Approaches to Measurements

Our teams came up with a strategy to address the theme of unlocking the climate record in the NPLD. The strategy is multifaceted and cannot be completed in a single mission.

The first part of the strategy is to learn about the fluxes of materials into and out of the polar regions. These are the materials that comprise the bulk of what is stored in the PLD, and it is of utmost importance to their availability on daily, seasonal, and inter-annual timescales. Portions of this topic must be addressed from orbit because point data from the surface will only supply a limited knowledge of polar fluxes. However, surface data is also a requirement in order to get high resolution at the lowest scale height in the atmosphere (ground truthing of orbital data) and at the surface-atmosphere boundary. An orbital component is also necessary to survey all of the volatile reservoirs on Mars that interact with the atmosphere.

Surface-based observations are necessary to determine the chemical and physical nature of the layers themselves. Our team has come up with a series of missions, of increasing complexity, that will move towards determining the climate record. This series was decided because some initial reconnaissance of available materials must be done before sending the finest precision, mobile instruments. For example, we don't know the isotopes available in the polar ice, so sending instruments that measure isotope ratios at high precision is not warranted until those isotopes have been shown to exist in sufficient quantities for accurate measurement.

The series of missions that we determined include 1) Discovery or New Frontiers Class static lander capable of measuring surface and subsurface properties using a meter class drill and atmospheric properties; 2) several small landers that have instruments to either measure the atmospheric or surface properties; and 3) a large, Flagship Class mobile platform capable of accessing the many layers exposed in a spiral trough or at a polar scarp. The instruments for the mobile platform may be baselined now, but the final selection should be based on what materials have been measured in previous missions.

3.C.1 Orbiter

An orbiter mission dedicated to the study of the martian polar regions has the potential to greatly advance our understanding of the present day forcings and fluxes in and out of the high latitudes, and also help characterize fundamental properties of the PLD themselves. An orbiter would have the advantage of providing data over the entire planet, possibly across multiple martian years, including during winter seasons. In addition, we note a landed mission making similar measurements would complement this suite by providing "ground truth" data.

Complete coverage of the planet and at all local times would be ideal, but with a single orbiter trades must be made. A 90° inclination would reduce data gaps at the poles (as opposed to ~87/93° as for MGS, ODY, and MRO). However, this reduces coverage at other parts of the planets. In addition, an orbital configuration allowing for a range of local times would be

Figure 3.1: Orbiter schematic showing a spacecraft with large radar reflector and extended solar panels to support a powerful suite of instruments (google search).

desirable (as opposed to the fixed AM/PM orbits of MGS, ODY, MRO) in order to gain access to diurnal processes on the ground and in the atmosphere, and further enhance the scientific value of existing datasets. However, access to various local times often comes at the expense of orbital coverage at the poles. On the other hand, increasing the baseline of current atmospheric observations with Mars Climate Sounder (MCS) and MARCI is also desirable.

An elliptical orbital configuration would allow for a low periapsis (~150 km) over the pole to be studied. The use of solar-electric propulsion and orbit changing maneuvers could enable the orbiter to alternate between periapsis at the North and the South caps in different Mars years or strategically selected seasons.

The science payload could be composed of instruments selected to fit within one of two broad themes: 1) Fluxes and Forcings, and 2) PLD Physical Properties. We note that several instruments have a very strong flight heritage and could potentially be proposed with modest technological investments. See Table 2 for a list of instrument type and key measurement goals.

Fluxes and Forcings

Of highest priority is to measure global wind speeds at Mars. This measurement has never been made and represents one of the largest strategic knowledge gaps in our understanding of present martian climate. We foresee two instruments supporting this priority, a microwave sounder or a LIDAR. Besides measuring wind speeds, either could provide profiles of temperature, water vapor and other tracers in the atmosphere. This would provide a new benchmark for the performance of General Circulation Models. Together with a sounding

Table 2: Oriber Straw-man Payload

Orbiter Instrument Type	Key Measurement Goals	Performance Characteristics	Orbiter Platform(s)	Notes
Multi-Wavelength Visible Imager	Morphology, Albedo, Composition, Topography	Better than HiRISE, maybe 1 cm?	Small, Medium, Large	Could resolve thinner layers, Provides valuable context for other measurements
Near-IR Pushbroom Spectrometer	Composition – H2O Ice, CO2 ice, Dust	Better than CRISM	Medium, Large	Only works in the sunlight
IR Limb/Nadir Sounder	Vertical profiles of Temperature, Water Vapor, Aerosols	Better than MCS	Small, Medium, Large	Connects polar deposits with global atmospheric processes
Microwave Nadir Sounder	Vertical profiles of Temperature, Water Vapor, CO and other tracers, Surface Temperature and Dielectric Properties	1 km? horizontal resolution	Small, Medium, Large	Complementary to IR sounder – no aerosol sensitivity
High-Resolution RADAR Sounder	Map PLD layers at high resolution	10 cm vertical resolution 100 m penetration (300 MHz)	Medium, Large	Complementary to MARSIS and SHARAD
Multi-Wavelength LIDAR	High-resolution topography, CO2 and H2O composition, Seasonal and interannual variabiltiy, cloud profiles	<1 cm vertical resolution, <5 meters horizontal resolution, >4 wavelengths, atmospheric profiling capability	Medium, Large	Works at night, Could measure annual CO2 accumulation and sublimation, and possibly PLD erosion and accumulation rates. High precision orbit required.
INSAR	Temporal changes in topography, surface roughness	< 1 cm resolution	Medium, Large	Works on Earth to measure glacier flow and interannual variability. High precision orbit required
Microwave or LIDAR Wind Profiler	Winds	TBD	Medium, Large	Real game-changer for GCM realism, Polar vortex studies etc.

instrument, a wind profiler with coverage in the lowest scale height would provide complementary capabilities to link transport of atmospheric constituents simultaneously to wind speeds.

- An IR sounder inspired by MCS and dedicated to characterizing the polar atmosphere would provide temperature, water vapor, dust, CO_2 and H_2O ice cloud profiles as well as surface temperature and emissivity. Improvement in order to obtain high vertical resolution and better coverage in the lowest scale height (close to the surface) are important.

PLD Physical Properties

- A sounding mode radar P- or L- Band frequencies could resolve fine layering sequences within the top 100s of meters of the PLD with a high vertical resolution of ~50 cm. Such an instrument would be complementary to MARSIS and SHARAD and could help explore the most recent few hundreds of thousands of years worth of record in the PLDs.

- Very high spatial resolution imagers (multi-wavelength visible, similar to HiRISE, and hyperspectral visible /near IR spectrometers, similar to CRISM) would have the potential to resolve finer layer structures within the stratigraphic record, and constrain their composition. We note that to generate fundamentally new science information, the spatial resolution of these instruments would need to be at least an order of magnitude better than HiRISE and CRISM.

- An Synthetic Aperture Radar (SAR) instrument with interferometric capabilities (InSAR) on the order of 1 cm could determine vertical changes of surface topography at the poles (mass wasting or seasonal accumulation) giving the potential to characterize the current imbalance in the energy budget of the caps. This instrument, while being highly valuable for polar observations, would also provide a new dataset for the entire planet, changing the way scientists study martian geology.

- Finally, a multipurpose LIDAR instrument could provide valuable surface and atmosphere science, with high-resolution topography (vertical resolution better than 1 cm desirable to detect surface changes and help characterize fluxes towards or out of the PLD at the seasonal and inter-annual time scales). Multiple wavelengths could allow the characterization of surface CO_2 and water ice optical properties. It could also be used to detect and characterize clouds within the polar night.

Hybrid orbital/surface missions could also be considered. Surface assets may be able to provide ground truth to calibrate regional datasets (for example for the study of volatiles or dust fluxes at the surface) and be able to deploy surface calibration targets, reflectors, or radio beacons to improve the accuracy and precision for monitoring of changes. Impactor missions could gather data during descent and provide extremely high spatial resolution of surface and near surface properties, well beyond what can be achieved from orbit. Finally, inspired from terrestrial glaciology, an instrument could disperse a dye on the surface. The changes (color, albedo, etc.) as characterized from orbit could prove a means to determine the mass balance at multiple locations.

3.C.2 Static Lander

Observations from the surface are invaluable for in situ comparisons, providing ground truth and higher resolution than measurements capable from orbit. At the surface, numerous experiments can characterize atmospheric, surface, and subsurface properties and processes. This is absolutely required to complete the stated purpose of this study.

A network of similar platforms to make these measurements from the surface is ideal; however, this type of mission may be larger than even a Flagship class, and so we discuss a straw-man payload for a single static lander, keeping in mine the desire to repeat these measurements at several sites simultaneously.

Landing site choice will be influenced by 1) safety to the mission and 2) completing our science requirements. If all sites are determined to be equally safe, then the optimal landing site will be one that maximizes science returns. Because the mission is to understand subsurface layering, atmospheric processes, and surface-atmosphere interaction, locations with greater surface-atmosphere activity (e.g. high mass balance and wind speeds) are preferred. Another important consideration is subsurface layering. It is undesirable to choose a location that has unique or local processes that do not represent the wider PLD or general behavior. This excludes locations near the bottom of the spiral troughs, where dust and ice accumulate more quickly than in other regions do to local atmospheric effects (Smith et al., 2013).

We anticipate that a static lander is best suited as a reconnaissance mission designed to characterize the environment at the NPLD. This first delivery to the NPLD surface should include instrumentation that is capable of addressing strategic knowledge gaps, including measuring all relevant atmospheric parameters and processes, observe surface changes and properties at variable scales, and access the near subsurface, or the top 100 cm. This mission should be of the NASA Discovery or New Frontiers class and provide the groundwork for future a Flagship

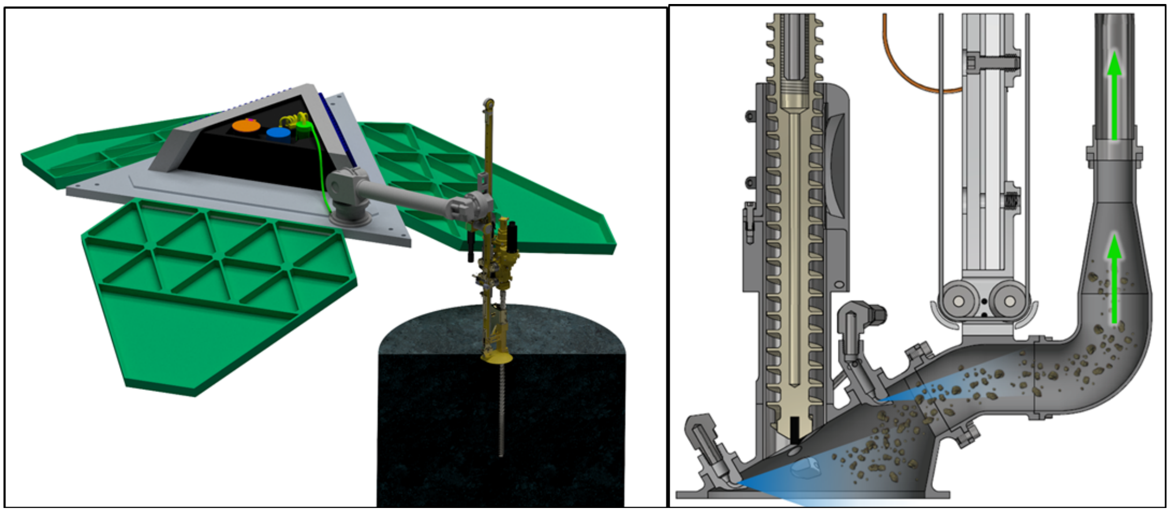


Figure 3.2: CAD rendition of a lander asset using the MER EDL architecture. A) A drill arm extends past the landing hardware and mechanically drills ~50 cm into the subsurface using several small steps. B) Pneumatic hardware moves the drill cuttings to the lander deck where they can be analyzed by onboard instruments. Graphic courtesy of Honeybee Robotics

mission (see section *3.C.4)* designed advance the knowledge gained.

A payload that characterizes the uppermost 100 cm of ice will require access to that depth. Potential methods to do so include thermal or mechanical drilling and analysis inside the borehole or analysis of material brought to instruments on the lander deck. Some instruments

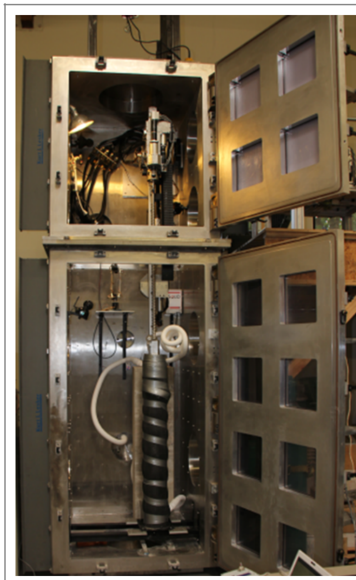


Figure 3.3a: Honeybee's Icebreaker drill successfully penetrated ice with perchlorate under mars pressure and temperature conditions.

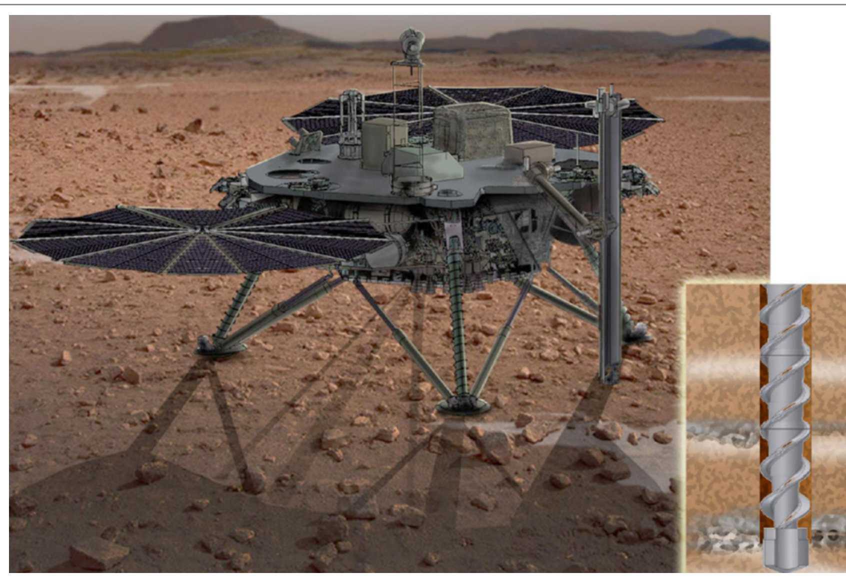


Figure 3.3b Icebreaker mission would land in the Northern Polar Regions and deploy 1 m class drill.

are too large to fit in a borehole, making in situ analysis infeasible, so a combination of techniques is considered.

Here we concentrate on an approach that includes a mechanical drill, as opposed to a melt-probe. The main driver for using a mechanical drill is the significant power savings. Cryogenic ice is 3-4x more conductive than warm ice, and as such, the melting approach is extremely inefficient (>80% of heat is lost into surrounding ice). This would warrant development of fission reactor to supply power. Additionally, melt probes would alter the material (and in turn reduce its science value) and would not be able to penetrate material with significant dust fraction.

Modifying the drill string to include instruments would add significantly more effort, cost, and risk. Instead we assume that the drill string (with some limited sensing capabilities) would be pulled out of the hole to allow a logging tool with analytical suite to be lowered back in. The cuttings generated during the drilling process would be returned to and analyzed by even more capable lander-based instruments. This all implies, there are three possible approaches to the investigation: 1. Sensing while drilling, 2. Logging the borehole and 3. Analyzing drilled samples, a 3-tier approach that optimizes science return and reduces risk.

Sensing while drilling is the first approach. Drill-integrated instruments that would help with the drilling process, reduce mechanical risks, and provide science data. The instruments and data include:

- Material strength and density from drilling telemetry
- Density from ultrasonic velocity
- Subsurface temperature from temperature sensor
- Bulk electrical resistivity (required to detect “slush” formation but also indicative of salt content) from resistivity sensor

Additional instruments could also be packaged inside a drill string, but the extent of what can be included largely depends on the diameter, and robustness to shock, vibrations and temperature. Examples of drill integrated instruments include microscopic imager, LIBS and deppUV/Raman. Some of these systems reached high TRLs. Other sample acquisition options include acquiring a sample downhole and volatilizing it inside a drill bit. A carrier gas could then carry evolved or trapped gasses directly into a GC/MS on the surface. Instruments could also be placed close to the borehole itself and sniff for any volatiles coming off the pile of cuttings. The Resource Prospector rover has successfully implemented Near Infrared Spectrometer that looked at cuttings as these were being brought up to the surface by the drill.

For instruments lowered into the bore hole after drill and cutting extraction, we envisioned the logging (in situ analysis) package to contain:

- optical camera system
- microscope
- fine-scale electrical resistivity probe
- temperature sensor

The optical camera system should provide a wide field of view (analogous to a fish-eye lens) and together with a temperature sensor should address most of the questions associated with “borehole logging”. The microscope may have a short working distance and thus be able to reach sub-micron resolutions. Both the optical camera and the microscope will require some form of illumination system (e.g. multi color LEDs). In addition, we foresee the inclusion of laser in the borehole as a source for performing Laser Induced Breakdown Spectroscopy (LIBS) and deepUV/Raman. The spectrometer would reside on the deck of the lander and be fed via fiber-optic cable, while laser would be integrated with a drill. Placing a laser in a logging tool itself will

Table 3: Lander Instrumentation. Drill (D); Borehole Logger (BL); Lander Deck (LD)

Type of measurement	Instrument	Heritage	Location	Comment
Optical	Pan-cam (multi-spec)	Many	D, BL, LD	
Optical	Microscope	Many	D, BL	
Environmental	Ground penetrating radar		LD	
Environmental	Met station	Many	LD	
Environmental	Ice and dust accumulation system		LD	Quartz-crystal microbalance?
Environmental	LIDAR	Phoenix	LD	
Analytical	Tunable laser spectrometer	MSL	LD	
Analytical	Mass spectrometer	Phoenix	LD	Connected via a vacuum pump and tubing to the mouth of the borehole
Analytical	Deep UV, Raman or VNIR (with fiberoptic lead)	Mars 2020	D, BL, LD	Fibre-fed from the borehole
Elemental	LIBS	MSL, Mars2020	D, BL, LD	Fibre-fed from the borehole
Ice structure	micro CT			Examine Core

reduce a significant risk of fiber damage due to high power laser.

A further element would be the inclusion of a small side-drill designed to penetrate specific layers identified by the optical camera. This "borehole sampler" would capture a small volume of material from a specific location in the borehole, identified to be of interest by other instruments (e.g. LIBS or Raman). This sample would then be analyzed with, for example, a mass spectrometer on the lander deck.

Finally, we note that significant science can be achieved by analyzing samples in instruments that are too difficult or impossible to package into a long and slim tube (i.e. to fit inside a drill or a logging tool). Many of these instruments or science packages exist – the best example is the Sample Analysis at Mars (SAM) instrument onboard of MSL rover.

We also note a strong interest in using the micro-CT technique to study the internal structure of the ice in a non-destructive manner. This could be achieved by producing a core rather than an empty borehole. A miniaturized micro-CT would then be placed around the core or the core drill to make the measurement. It is clear that this idea has several technical challenges to overcome (e.g. maintenance of the integrity of the core during drilling and development of the instrument itself) but the scientific return appears to be sufficient to warrant further study. Some form of nepholometer might also be considered, or alternatively a micro-CT could be performed on large ice chips that will be produced during drilling.

Borehole Drilling

Drilling in cryogenic environments is difficult and not yet proven. There are numerous technical challenges to overcome:

a. *Sampling resolution*

Layering of the PLD may be as fine as 0.5 mm, and therefore investigations should approach this resolution. However, data acquisition with this level of spatial resolution would be difficult to impossible with robotic sampling because of data volumes are much higher and the time required to perform the experiment is too long. Hence, we envision selecting positions down the borehole for high resolution investigation. Elsewhere, lower vertical resolution acquisition along the column would be performed. This implies that a robust operations concept will be necessary with ground interaction in the loop to finalize the experiment plan.

b. *Instrument integration and resources*

Instrument capable of performing the proposed tasks do not yet exist. Therefore, miniaturization technology is probably needed, and accommodation and further trade-offs and de-scopes may be required, depending on the size of the landing platform and budget.

c. *Removal of drilled material*

The smallest useful diameter of the borehole is likely to be around 5 cm. Thus, at least 7,500 cm^3 of material will need to be removed from the borehole. This material needs to be dumped close to the lander or transported by some means to the lander deck. The dumped material may alter before measurements are made. For examples ice may sublimate, leaving fines or

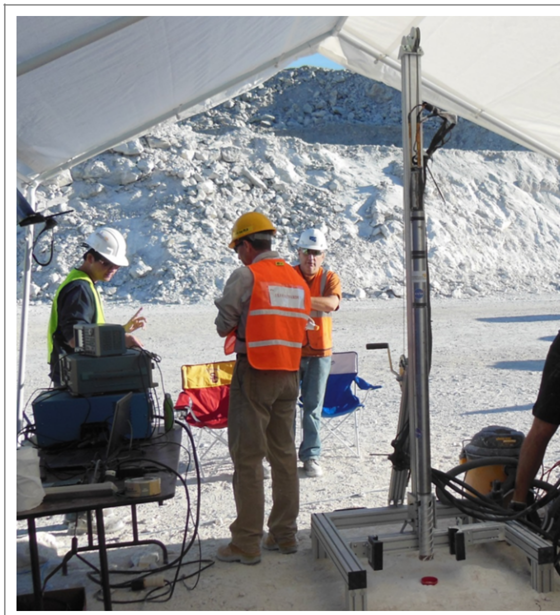


Figure 3.4. Honeybee/JPL Autogopher1 drill penetrated to 3 m depth in hard gypsum and captured cores. Core breakoff and retention was proven to be difficult because often cores would breakup along weak layers.

dust unbound. This may become mobile (blown away by wind) thereby affecting measurements.

d. *Borehole integrity*

Material may fall into the borehole, affecting continued drilling and sample knowledge.

e. Re-condensation within the borehole

The drilling process generates heat that can lead to the sublimation of volatiles close to the drill bit. The gas produced can then re-condense on the colder walls of the borehole interfering with measurements.

f. Sediment layer

The mixing ratio of non-volatile material in individual layers is uncertain. This may affect drilling operations. Newly exposed dust may be mobilized, affecting measurements.

g. Diffusive loss of trapped gases

h. Other ice evolution

Assessment of how the ice evolves after it becomes exposed (in the borehole or the cuttings on the surface) is required. This involves volatilization or recrystallization.

Justification for rejection of specific alternatives

a. Coring and core extraction

The technical challenges in implementing an automated coring system and maintaining the integrity of the core throughout extraction and analysis are substantial. Core integrity may suffer from fracturing and loss of cohesion if sections are loaded with un-cemented material.

b. Analysis of chips from the drilling process

Ice splinters or chips will be produced by the drilling process. These chips can be collected and brought to the deck instruments for analysis. This operation, for example, is being done on Curiosity and numerous missions baseline chips for analysis by the science instruments; however, exact knowledge of the former burial depth will be difficult to record.

3.C.3 Small-Sat Network

Besides an orbiter and static lander, numerous options are available for small-sat, short-lived missions that can perform rapid measurements while being scattered over the NPLD. In particular, the $\text{Mars}_{\text{Drop}}$ platform is of interest (Staehle, et al., 2015). These units are approximately the size of a 6U cubesat and shaped like an ice-cream cone. The dome carries a parachute but no other EDL components. Landing on a target more specific than the 1000 km diameter polar cap is not required. Once on the surface, several solar panels would deploy, revealing the payload.

Because of their small size, $\text{Mars}_{\text{Drop}}$ spacecraft must contain targeted investigations. Multiple missions of this scale could be sent simultaneously to measure atmospheric properties, atmospheric constituents, or surface and subsurface properties. For the atmosphere, a sonic anemometer coupled with temperature, pressure, and humidity instruments would be a desirable addition to the meteorological network scattered across the polar landscape. Sending a TLS to measure the atmospheric components could also be of high value. Finally, a package that is able to measure ice properties would significantly contribute to the mission science. Examples include electro-conductivity or ground penetrating radar that could fit within the $\text{Mars}_{\text{Drop}}$ package.

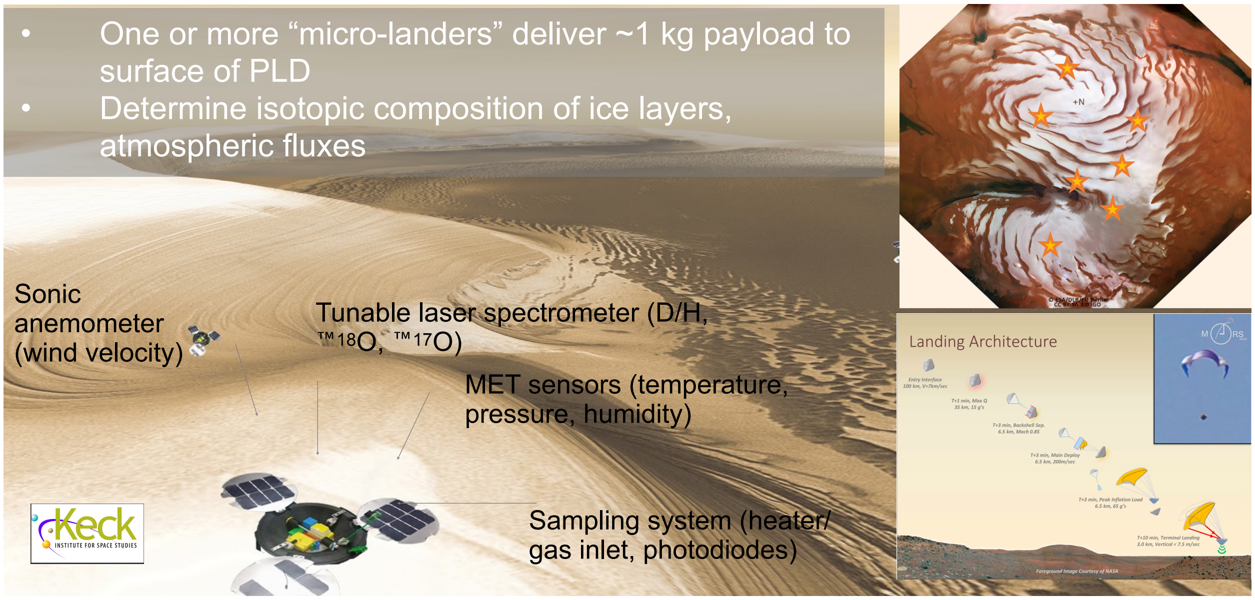


Figure 3.5: Deployment of a network of small-sat MarsDrop spacecraft carrying either atmospheric or surface measurement instrumentation.

3.C.4 Mobile Platform

Once a static lander mission is complete, and we have more information about the composition of the non-ice materials in the PLD and their abundances, the next step would be to deploy a mission capable of sampling significantly deeper than ~1 m. Two options are available for accessing >100 m of ice. Both would carry updated instrumentation based on the knowledge gained from the previous, static lander. The first option includes a 100 m class drill. The second includes a mobile platform with a 1 m drill. The 100 m class drill would be mounted on a static lander and penetrate to the target depth, while providing samples to the lander mounted instruments and deploying downhole instruments. The mobile platform would traverse the gently sloping outcrops of spiral troughs to sample many layers. Given sufficient duration, this mission could repeat multiple transects, enhancing our knowledge of the layers.

The mission would likely fall into the Flagship class and carry numerous scientific instruments for a highly capable payload. The rover could leverage high heritage from several components of the Curiosity rover, reducing cost and improving reliability. An instrument suite on a flagship rover would likely carry several instruments: a stereo imager; meteorological station, and a 1-meter class drill. The stereo imager would assess layer thickness and frequency, assess surface conditions, and help with terrain navigation. The meteorological package, similar to the met station on the stationary lander, would continue atmospheric science at a new locations. The 1-meter class drill would be used to access material beneath the surface, which is likely covered by a lag several to tens of cm thick.

Additional instruments would be selected after results from the previous static lander were interpreted. We stress this strategy because sending instruments on an expensive mission will only be valuable if the materials to be measured are known to be of sufficient abundance to make the cost worthwhile. With that said, we believe that some or all of the following suite will provide necessary measurements to help unlock the climate record stored in the NPLD. On the rover deck, we envision carrying a ground penetrating radar and chemistry suite encompassing wet geochemistry and a mass spectrometer. For down-borehole measurements, we envision carrying an optical imager (for grain size and layer thickness), MI (for grain size and layer thickness), thermal and electrical conductivity, tuning laser spectrometer, nephelometer (for particle size distribution of impurities in the ice), Micro-spectroscopy, and microCT.

Measuring the composition of each layer, including the ratio of datable isotopes is of utmost priority. Besides dating the layers, some measurements that may be possible include ^{10}Be, D/H, ^{18}O/^{16}O. Having D/H through time may be one of the greatest measurements we can make. It would also be valuable to determine if other isotopes can provide information about climate processes. Some of the technological issues that will need to be overcome include drilling (from a rover or a lander), mobility in a polar environment (in the case of a rover

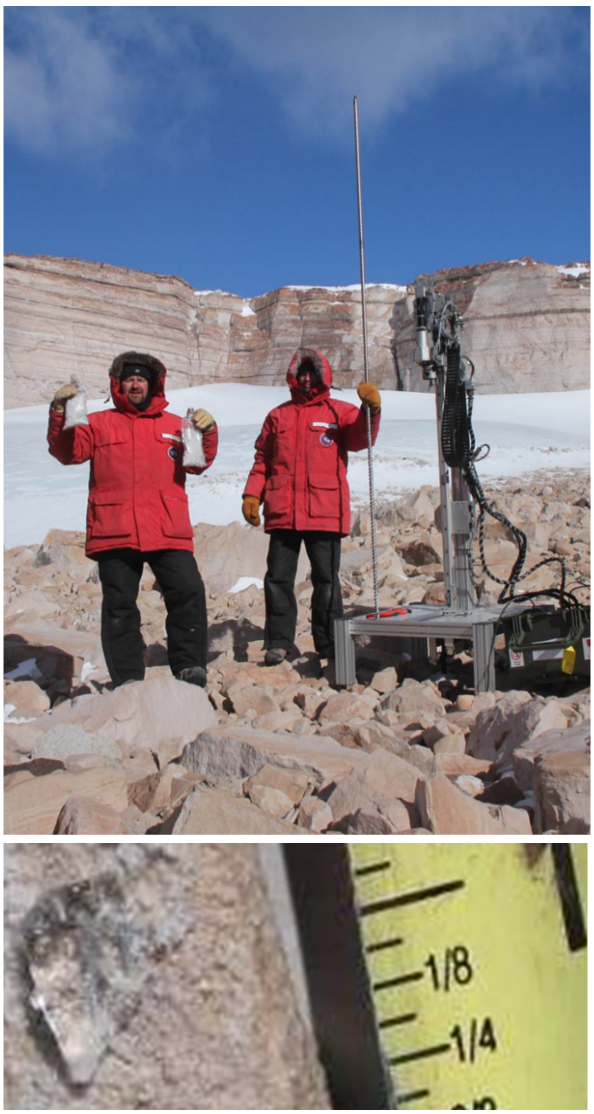


Figure 3.6a: Honeybee's Icebreaker penetrated 2 m in 2 hours in Antarctica. Ice chips as large as 0.25 inch were captured.

Figure 3.6b: Honeybee/JPL AutoGopher2 drill reached 7.5 m depth in 40 MPa gypsum

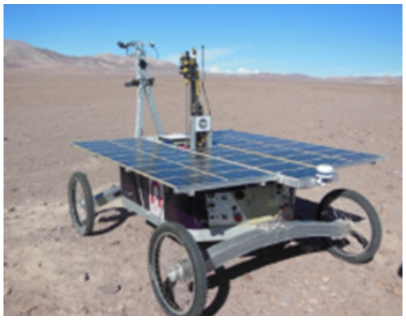
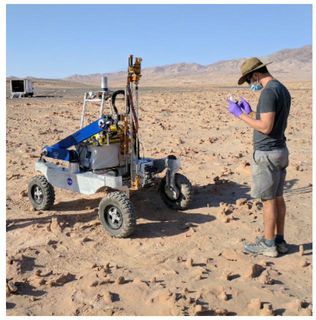
		
Honeybee LITA drill on CMU Zoe rover	Honeybee ARADS drill on NASA Ames KREX2 rover.	Honeybee TRIDENT drill on NASA JSC Resource Prospector rover.

Figure 3.7. Several drills were deployed on various rovers.

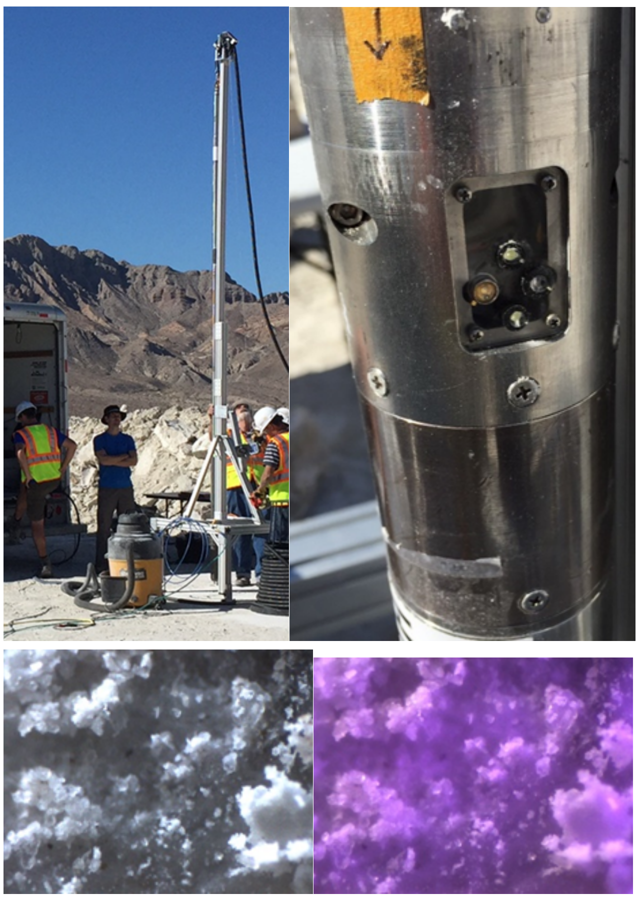
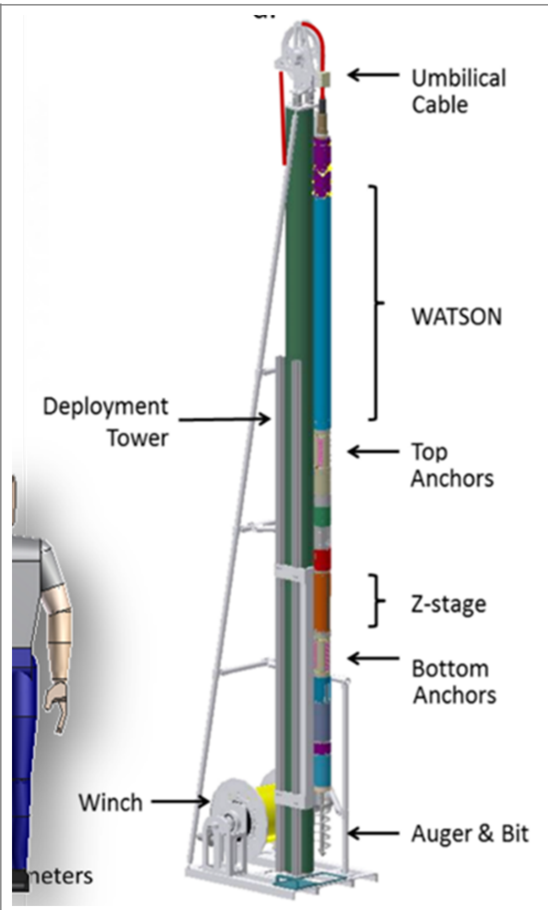


Figure 3.8a. Honeybee's Planetary Deep Drill penetrated 13.5 m and 10.5 m in hard gypsum over a 5 week duration. The drill took borehole pictures with a 0.5 micron/pixel microscope and two color LEDs (UV and white).



Honeybee/JPL WATSON drill incorporates Mars2020 SHERLOCK instrument (Deep UV/Raman)

platform), and surviving a polar night.

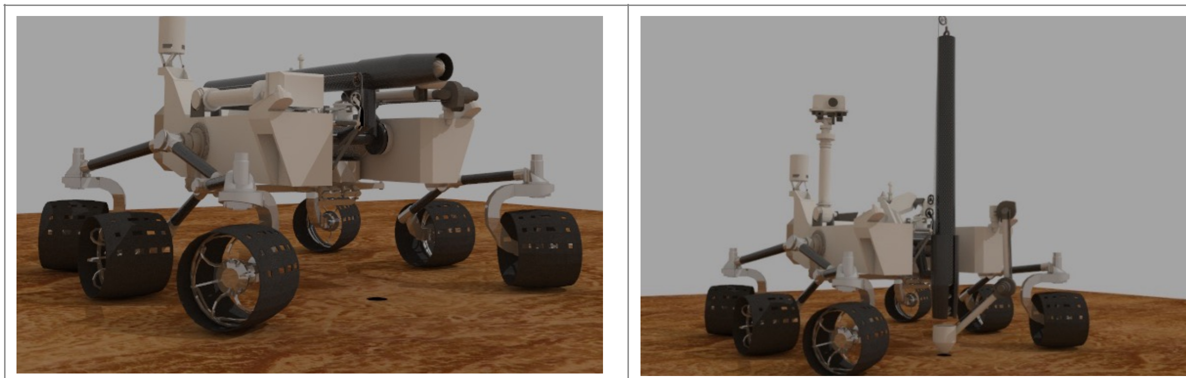


Figure 3.9. Deep drill could potentially be placed on a rover to allow for better site selection.

List of Acronyms

APXS	Alpha Particle X-ray Spectroscopy
CFA	Continuous Flow Aparatus
CRISM	Compact Reconnaissance Imaging Spectrometer for Mars
CTX	Context Camera
DTM	Digital Terrain Model
ECM	Electrical Conductivity Measurement
FRAM	Far Roving Arctic Mission
FTIR	Fourier transform infrared
GCM	Global Climate Model
GPR	Ground Penetrating Radar
GRS	Gamma Ray Spectrometer
HiRISE	High Resolution Imaging Science Experiment
HRSC	High Resolution Stereo Color Imager
IRIS	Infrared Interferometer Spectrometer
IRTM	Inrafred Thermal Mapper
KISS	Keck Institute for Space Studies
LIBS	Laser-induced Breakdown Spectroscopy
MARCI	Mars Color Imager
MARSIS	Mars Advanced Radar for Subsurface and Ionosphere Sounding
MB	Marker Bed
MCS	Mars Climate Sounder
MGS	Mars Global Surveyor
MOLA	Mars Orbiter Laser Altimeter
MOC	Mars Orbiter Camera
MRO	Mars Reconnaissance Orbiter
MSL	Mars Science Laboratory
NPLD	North Polar Layered Deposit
OMEGA	Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité
PFS	Planetary Fourier Spectrometer
PLD	Polar Layered Deposit
RAT	Rock Abrasion Tool
RIMS	Resonance Ionized Mass Spectrometry
SAM	Sample Analysis at Mars
SAR	Synthetic Aperture Radar
SHARAD	Shallow Radar sounder
SFD	Size-frequency Distribution
SPLD	South Polar Layered Deposit
TES	Thermal Emission Spectrometer
TLS	Thin Layer Sets
THEMIS	Thermal Emission Imaging System
WRAP	Widespread Accumulation Package
XRF	X-ray Fluorescence

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